NASA CONTRACTOR REPORT

N73-15858
NASA CR-2160

NASA CR-2160

CASE FILE COPY

EXTRAVEHICULAR ACTIVITIES GUIDELINES AND DESIGN CRITERIA

by Nelson E. Brown, Thomas R. Dashner, and Benita C. Hayes

Prepared by
URS/MATRIX COMPANY
Huntsville, Ala. 35805
for George C. Marshall Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1973

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA CR-2160	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Extravehicular Activities Guidelines and Design Criteria		5. REPORT DATE January 1973
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Nelson E. Brown, Thomas R. Dashner, and Benita C. Hayes		8. PERFORMING ORGANIZATION REPORT # M601
9. PERFORMING ORGANIZATION NAME AND ADDRESS URS/Matrix Company 4702 Governors Drive West Huntsville, Alabama 35805		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO. NAS8-27502
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20546		13. TYPE OF REPORT & PERIOD COVERED Contractor Report
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Considerable expertise in orbital Extravehicular Activity (EVA) planning, development, and operation has been accrued by both NASA and industry; these data were, however, seriously fragmented. This report combines into a single source, orbital EVA information considered useful to many engineers, mission planners, and designers associated with future manned space programs. The document defines the various extravehicular (EV) operating modes, summarizes the EV environment, presents the story of orbital EVA and summarizes the conclusions derived from these experiences.

The document contains a listing of astronaut EVA support systems and equipment, and the physical, operational, and performance characteristics of each major system are presented. An overview of the major ground based support operations necessary in the development and verification of orbital EVA systems is included. The performance and biomedical characteristics of man in the orbital EV environment are discussed. Major factors affecting astronaut EV work performance are identified and delineated as they relate to EV support systems design.

Data concerning the medical and physiological aspects of spaceflight on man are included. The document concludes with an extensive bibliography, and a series of appendices which expand on some of the information presented in the main body. Information---including a brief history of advanced space suit development; an overview of the requirements for testing in a "zero-gravity" aircraft; an inventory of specialized conversions and factors; and a list of methods and procedures for determining metabolic rates during EVA, etc.---is presented. These data are included as an additional aid in planning and designing for future orbital extravehicular activities.

17. KEY WORDS Manned Spaceflight, Extravehicular Activity (EVA), EVA Equipment, EVA History, Space Tools, Human Performance in EV Space, Space Suits, Life Support Systems, Spaceflight Medical Experience, Space Cabin Contaminants, Metabolic Rates, Airlocks, Maneuvering Equipment, Worksites	18. DISTRIBUTION STATEMENT		
19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 574	22. PRICE $6.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

Contained in the Extravehicular Activities Guidelines and Design Criteria document is a compendium of data concerning manned spaceflight orbital Extravehicular Activities (EVA). State-of-the-art developments in EVA support systems and equipment, operational techniques, guidelines and constraints, and EVA equipment characteristics of specific importance to manned EVA missions are presented along with human performance characteristics in the orbital EVA environment. Spaceflight biomedical and physiological aspects, as they relate to extravehicular activities, are also discussed. Although other systems, such as those using automation and teleoperators, provide alternatives to performing EVA, information on these systems is limited in EVA Guidelines, since these techniques are not the main focus of this document.

The primary purpose of EVA Guidelines is to present the engineer, mission analyst, and designer with data to efficiently aid in providing an initial solution to his EVA design problem, once the requirement for orbital manned EVA has been established. Information contained in the document should be especially useful to the Shuttle and RAM (Research and Applications Module) study programs and should be applicable to all future manned spaceflights. While this document is not intended to be a text or detailed design manual in the usual engineering sense, an extensive bibliography is included for those requiring additional detail in specific areas.

The material presented in this document resulted from an extensive and systematic survey of scientific and technical documentation in the area of orbital EVA. The information contained herein is a synthesis of this documentation. Because of the rapid advancements in aerospace technology, new materials, advanced systems, etc., this document will never be complete. The many aerospace research and technology study programs that are continuously being conducted preclude the maintainance of a completely current document.

PREFACE

The successful employment of manned EVA in the Gemini and Apollo Programs and its planned use on Skylab has established EVA as an operational mode for performing orbital mission functions outside the spacecraft. While remote manipulator systems and automation may provide feasible alternatives to performing manned EVA, human judgment and "real-time" decision making are key man versus machine selection factors. Man has demonstrated that he can be an integral part of the spaceflight EVA complex by adding the elements of judgment and reliability -- performance characteristics which are not provided through the use of mechanical/automated systems alone.

Since EVA capability is a requirement for many manned orbital missions, it is desirable to provide the mission planner, designer, and engineer with a central source of information concerning EVA systems and equipment. The EVA Guidelines provides a compilation of specialized EVA human performance data and equipment characteristics which may be used to aid in the selection and design of EVA systems for future spacecraft. The use of the document should also assist mission specialists in utilizing man's capabilities to perform useful and essential extravehicular operations.

The first chapter introduces EVA, defines the various operating modes, and summarizes the EVA environment. The history of EVA is briefly presented in the chapter, along with a summary of the conclusions derived from these experiences. Although the document is basically concerned with orbital EVA operations and equipment, lunar EVA experience is included in Chapter I because of similarities that exist between orbital and lunar EVA with relation to equipment, operations, and environment. Discussions of the EVAs planned on the remaining Apollo flights and those projected for Skylab and for the more distant space programs conclude the chapter.

Chapter II reviews the orbital EVA operations performed on past Gemini and Apollo flights for application to future EVA missions. An assessment of the operations performed on past EVAs, those planned for Skylab, and those derived from a survey of potential future missions has provided data for the identification, classification, and description of typical EVA functions. The EVA function classification covers currently projected EVA task applications on proposed orbital space missions. Chapter II also presents an extensive listing of manned EVA design/selection considerations, which must be weighed by the mission planner for each major system and subsystem required for EVA.

Chapter III is concerned with presenting sufficient information to tentatively select EVA support systems for future missions from currently available hardware. The chapter contains a detailed listing of astronaut EVA support systems and equipment, and equipment in the advanced development stage. Systems and hardware descriptions are provided, and the physical, operational and performance characteristics of each major system

and subsystem are presented, with special emphasis placed on the system performance characteristics. Should the present system or systems in the development stage be inadequate for future mission application, preliminary design guidelines are presented which may be helpful in the specification and early design phases of EVA hardware.

Chapter IV presents an overview of the major ground based support operations necessary in the development and verification of orbital EVA systems. In addition to on-orbit EVA astronaut support systems and equipment, ground based EVA support requirements must be carefully considered to assure total EVA success and astronaut safety. Requirements such as systems testing and flight qualification test programs, simulation and training requirements, training hardware and mockups, simulation and training facilities utilization, and development of operational procedures for each simulation, training session, and flight function must be acknowledged.

Chapter V focuses on the performance and biomedical characteristics of man in the orbital EVA environment. To include man in future extravehicular space activities, the mission planners and designers must be cognizant of the performance characteristics of the pressure-suited crewman in conjunction with his support systems and environment. Major factors affecting astronaut EVA work performance are identified and delineated as they relate to EVA support systems design. The chapter presents available data concerning such performance characteristics as man's mobility, stabilization, reach, visibility, force, and mass handling abilities in the orbital environment. Data concerning the medical and physiological monitoring requirements of the EVA astronaut are included.

The document concludes with a bibliography and a series of appendices which expand on some of the information presented in the main body. Information such as a summary of spaceflight medical experience, a brief history of advanced space suit development, an overview of the requirements for testing in the "zero-gravity" aircraft, a roll of specialized conversions and factors, a list of methods and procedures for determining metabolic rates during EVA, etc. is presented. These data are included as an additional aid in planning and designing for future orbital extravehicular activities.

ACKNOWLEDGEMENTS

This document was prepared under Contract NAS8-27502 for the Office of Life Sciences, National Aeronautics and Space Administration, by the URS/Matrix Man Systems Company, a division of the URS Systems Corporation, Huntsville, Alabama. Special thanks are extended to Dr. Stanley Deutsch (NASA Headquarters, Office of Life Sciences) and to Stanley Johns (MSFC), the NASA technical monitor of this contract, for their help in arranging for the completion of the document.

Material for this document was accumulated from many sources, with considerable support being provided by personnel at the NASA Headquarters, the Marshall Space Flight Center, the Manned Spacecraft Center, and the Ames Research Center. The authors are indebted to many individuals at these NASA centers for their contributions to the document.

The authors wish to thank the following members of the 1971 NASA Committee on Extravehicular Activities for their support in the document's development: S. Deutsch, W. B. Evans, and J. L. Cooper (NASA Headquarters); S. A. Johns (Marshall Space Flight Center); L. E. Bell (Manned Spacecraft Center); R. W. Stone, Jr. (Langley Research Center); C. C. Kubokawa (Ames Research Center); and G. C. Keller (Goddard Space Flight Center).

Special appreciation is due to the following individuals for their worthy suggestions, valuable data, and critique support: E. J. McLaughlin, Ph.D. and Col. R. R. Hessberg (NASA Headquarters); Maj. E. C. Whitsett, Jr. (U. S. Air Force); and D. C. Schultz, J. L. Lewis, Jr., F. J. DeVos, J. J. Kosmo, M. Rodriguez, Jr., and A. F. Smith (Manned Spacecraft Center).

EXTRAVEHICULAR ACTIVITIES GUIDELINES AND DESIGN CRITERIA

GENERAL TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd.)

LIST OF FIGURES (Cont'd.)

LIST OF FIGURES (Cont'd.)

LIST OF FIGURES (Cont'd.)

FIGURE PAGE

LIST OF FIGURES (Cont'd.)

LIST OF FIGURES (Cont'd.)

LIST OF FIGURES (Cont'd.)

LIST OF TABLES

LIST OF TABLES (Cont'd.)

LIST OF TABLES (Cont'd.)

ACRONYMS AND ABBREVIATIONS

A	Amplifier
Å	Angstrom
ACS	Attitude Control Subsystem
AEPS	Advanced Extravehicular Protective System
AES	Advanced Extravehicular Suit
ALSA	Astronaut Life Support Assembly
AM	Airlock Module
AMRV	Astronaut Maneuvering Research Vehicle
AMU	Astronaut Maneuvering Unit
AS	Adapter Section
ASMU	Automatically Stabilized Maneuvering Unit
ASSY	Assembly
ATM	Apollo Telescope Mount
BIRT	Bolt Installation and Removal Tool
BSLSS	Buddy Secondary Life Support System
Btu	British Thermal Units
CCA	Communication Carrier Assembly
CCU	Crew Communication Umbilical
C&D	Controls and Displays
C&DS	Controls and Displays Subsystem
CEA	Control Electronics Assembly
cfm	Cubic Feet per Minute
CH	Command Service Module Hatch
CM	Command Module
CMG	Control Moment Gyro
CMGA	Control Moment Gyro Assembly
CSM	Command Service Module
CTM	Cardiotachometer
CTS	Contingency Transfer System
C&W	Caution and Warning
CWG	Constant Wear Garment
DA	Deployment Assembly

DAC	Data Acquisition Camera
DCC	DC to DC Converter
DCS	Digital Command System
D/T TM	Delayed Time Telemetry
EA	Earphone Amplifier
ECG	Electrocardiogram; (or) Evaporative Cooling Garment
EC/LSS	Environmental Control and Life Support System
ECS	Environmental Control System
ECS/LS	Extravehicular Control System/Life Support
EEG	Electroencephalograph
EHA	Electrical Harness Assembly
EKG	Electrocardiogram
ELSS	Extravehicular Life Support System
EMU	Extravehicular Mobility Unit
ERI	Extravehicular Reference Information
ESP	Extravehicular Support Package
EV	Extravehicular
EVA	Extravehicular Activity
EVCS	Extravehicular Communications System
EVVA	Extravehicular Visor Assembly
Fac	Factor Instruction
FAS	Fixed Airlock Shroud
FCMU	Foot Controlled Maneuvering Unit
FCS	Fecal Containment System
FPE	Functional Program Elements
FTB	Film Transfer Boom
g	Gravity
GATV	Gemini-Agena Target Vehicle
GH	Gemini Hatch
GMT	Greenwich Mean Time
HHMU	Hand Held Maneuvering Unit
IEU	Interface Electronics Unit

IRI	Intravehicular Referenced Information
ITMG	Integrated Thermal Micrometeoroid Garment
IU	Instrument Unit
IVA	Intravehicular Activity
LBNP	Lower Body Nevative Pressure
LCG	Liquid Cooling Garment
LH	Lunar Module Hatch
LM	Lunar Module
LRL	Lunar Receiving Lab
LSU	Life Support Umbilical
MA	Mike Amplifier
MDA	Multiple Docking Adapter
MEED	Microbial Environment Exposure Device
MSFN	Manned Spaceflight Network
MWP	Maneuvering Work Platform
N/A	Not Applicable
NAB	Nut and Bolt Wrench
NAS-NCR	National Academy of Sciences - National Research Council
NM	Nautical Mile
NRZ	Nonreturn to Zero
OA	Orbital Assembly
OBS	Operational Bioinstrumentation System
OPLSS	Optimized Portable Life Support System
OPS	Oxygen Purge System
OWS	Orbital Workshop
PCM	Pulse-Code Modulation
PCU	Pressure Control Unit
PECS	Portable Environmental Control System
PGA	Pressure Garment Assembly
PGSU	Propellant Gas Supply Unit
PKG	Phonocardiogram
Plench	Pliers-wrench

PLSS	Portable Life Support System
PSS	Propellant Supply Subsystem
RAM	Research and Applications Module
RCVR	Receiver
RF	Radio Frequency
RGA	Rate Gyro Assembly
RHC	Rotational Hand Controller
ROMANS	Remote Manipulation Systems
R/T TM	Real Time Telemetry
S	Speaker
SA	Speaker Amplifier
SAS	Space Activity Suit
SC	Signal Conditioner
SCS	Suit Communications System
SEVA	Skylab Extravehicular Visor Assembly
SGA	Shirtsleeve Garment Assembly
SIA	Speaker Intercom Assembly
SID	Subject Identification Module
SIM	Scientific Instrument Module
SLSS	Secondary Life Support System
SOAR	Shuttle Orbital Applications and Requirements
SOP	Secondary Oxygen Pack
STEM	Storable Tubular Extendible Member
STS	Structural Transition Section
SW	Switch
SWS	Saturn Workshop
TBD	To Be Determined
TDA	Target Docking Adapter
TDY	Temporary Duty
TEM	Body Temperature Measuring System
THC	Translational Hand Controller
TLV	Threshold Limit Value

ACRONYMS AND ABBREVIATIONS (Cont'd.)

TRA	Tape Recorder Amplifier
TRS	Time Reference System
TYP	Typical
UCTA	Urine Collection Transfer Assembly
UV	Ultraviolet
VC	Center Workstation
VCM	Ventilation Control Module
VDC	Volts Direct Current
VF	Airlock/FAS Workstation
VS	Sun End Workstation
VT	Transfer Workstation
XMTR	Transmitter
ZPN	Impedance Pneumograph

CHAPTER I

INTRODUCTION TO EVA

TABLE OF CONTENTS

1.0 DEFINITION OF EXTRAVEHICULAR ACTIVITIES (EVA)

NASA's general definition of EVA refers to "any operation conducted by an astronaut while in a pressurized suit in a vacuum environment." Another definition of EVA for engineering purposes identifies EVA as being "operations carried out by a suited crewman at ambient pressures below 3.0 psia." Similar definitions of EVA were found in documentation concerning manned spaceflight activities. Most definitions of EVA encountered could include the interior of a depressurized orbital or lunar vehicle, or a ground based vacuum testing chamber. However, the NASA Committee on EVA established the definition of EVA as "activity performed in space or on a celestial body by an astronaut external to the space vehicle." (ref. 1.1) The space vehicle can be a spacecraft, space base, or extraterrestrial shelter. This document will adopt the EVA Committee's definition. EVA, as discussed here, will normally apply to activities conducted outside the spacecraft pressure hull, including areas such as an open Shuttle payload bay during orbital missions, and to activities exterior to the shelter during extraterrestrial missions. The definition of Intravehicular Activity (IVA) is presented to make clear the difference between extravehicular and intravehicular activities. The NASA Definition of IVA is "activity performed in space or on a celestial body by an astronaut internal to the space vehicle." This document considers these activities to range from shirtsleeve operations in the pressurized vehicle to space suited operations when the vehicle is depressurized. The pressure suited crewman, although subjected to a hazardous environment, is confined by the vehicle. Ground based simulation/testing, such as that done in thermal-vacuum chambers, is not considered extravehicular but, rather, as activity performed in a simulation of a hazardous space environment.

1.1 MODES OF EVA

Based on past EVAs and on those planned for future missions, the EVA operation modes have been defined as "umbilical" and "free." Also, EVA can support either planned, unscheduled, or contingency missions. Each of these classifications is defined as follows:

- UMBILICAL EVA is that EVA conducted by an astronaut while attached to the spacecraft by an umbilical. The umbilical provides both life support to the space suit and a restraint system for tethering the astronaut to the vehicle. In the umbilical mode, a self-contained, backup life support system is normally worn by the astronaut when he egresses the vehicle; this system is optional for open hatch or standup EVA. The backup system provides sufficient oxygen and suit pressure for the astronaut to safely ingress the vehicle if the primary (umbilical) life support system were to fail.

- FREE EVA is that EVA conducted by an astronaut with no life support connection to the space vehicle or extraterrestrial shelter. He may be either tethered to the vehicle, as in orbital EVA, or untethered, as in lunar surface exploration. The life support system normally consists of a self-contained backpack unit (current technology) carried by the astronaut. An independent contingency life support system(s) is worn by the astronaut.

- PLANNED EVA is designed into a mission flight plan for the purpose of fulfilling an objective of that mission. The objectives may range from demonstrating the capability to perform EVA, as on the initial Gemini flights, to the retrieval of solar astronomy film data, as scheduled for the Skylab program.

- UNSCHEDULED EVA is EVA which is performed only as required to ensure mission success. It is a backup method to complete a planned mission activity or to perform unscheduled repair/maintenance functions on noncritical spacecraft equipment. (Noncritical spacecraft equipment is that which will not jeopardize the astronauts or result in a contingency status should the equipment fail to operate.) Operational procedures are developed for on-orbit use for each operation that could feasibly involve unscheduled or contingency EVA (defined below).

- CONTINGENCY EVA is performed to repair, refurbish, or maintain either the spacecraft structural equipment or systems critical to the safety of the astronauts. Contingency EVA may be required as a result of one or more failures directly related to spacecraft systems or EVA support equipment and will utilize specific contingency procedures. Contingency EVA also encompasses astronaut transfer from a disabled spacecraft to a rescue vehicle.

1.2 EVA ENVIRONMENT

The space and extraterrestrial environments present survival problems to the EVA astronaut. In providing for the safety of the astronaut while he is pressure suited and working in these hostile settings, mission planners and designers must deal with several characteristic aspects of the orbital and lunar EVA environments. Attention must be focused on:

- the near perfect vacuum of such environments. The pressure (vacuum) environment is approximately 10^{-14}mm Hg.

- the temperature extremes. The earth orbital temperature range is -200°F to +160°F. The lunar surface temperature range is about -290°F to +300°F.

- the reduced gravity field. In earth orbit, this is considered to be zero; on the lunar surface, it is 5.4 ft/sec^2, which is a-proximately 1/6 of the earth's gravity.

- the micrometeoroid flux. The EVA astronaut is protected from the impact of micrometeoroids by his pressure suit, which is designed to function under the following conditions:

	MICROMETEOROID PROPERTIES	
PARAMETER	PRIMARY	SECONDARY
Velocity	18.6 miles/sec.	0.124 miles/sec.
Diameter	0.012 in.	0.094 in.
Density	0.018 lb./in.^{3}	0.126 lb./in.^{3}

- the electromagnetic radiation. The radiation environment of space is a mixture of electromagnetic energy and both ionizing and non-ionizing particulate matter. Of importance in safe EVA operations is protection from ionizing radiation, which includes (a) solar, galactic, and extra-galactic cosmic rays, (b) x-rays and gamma rays from the sun, solar flare and solar wind particles, (c) electrons and protons of the Van Allen Belts of trapped radiation, and (d) neutrons and alpha particles. Ionizing radiation imparts damage at the cellular levels in humans.

  The non-ionizing radiation consists of infrared and ultraviolet light from the sun, visible light, and microwaves in the radiofrequency spectrum. These radiation forms are effectively blocked or attenuated by the spacecraft or Pressure Garment Assembly (PGA) and pose no great hazard to the crewman.

  Relatively little is known about the specific effects of electromagnetic fields on man. The physiological mechanisms of such fields have not been explained completely, which means that magnetic fields are one of the unknowns among the potential stresses and hazards of spaceflight (ref. 1.2).

It is clear, therefore, that the crew's Pressure Garment Assembly and associated life support systems, in addition to supplying needed oxygen and ventilation and providing a positive pressure to prevent the boiling of body fluids and other associated tissue damage, must also provide protection against the thermal, micrometeoroid and radiation conditions that are encountered by astronauts during EVA.

The EVA Guidelines document places emphasis on the equipment the astronaut needs in order to work safely and effectively in the EVA environment, rather than on detailed data on the environment itself or on the astronaut's responses to the EVA environment. Essential environmental data has already been compiled in The Natural Environment and Physical Standards for the Apollo and Apollo Applications Programs document, M-DE 802008B, which contains information describing the gravitation, pressure, radiation, and thermal environments of

orbital, lunar, and interplanetary spaces. Data concerning human responses to the EVA environment are contained in the following documents:

- Compendium of Human Responses to the Aerospace Environment, Vols. I, II, and III, NASA CR-1205, Lovelace Foundation for Medical Education and Research, 1968.

- Bioastronautics Data Book, NASA SP-3006, Webb Associates, 1964.

1.3 HISTORY OF EVA

EVA can be divided into three subgroups: orbital, lunar and interplanetary. To date, missions during which EVA was accomplished in an orbital trajectory have been the Gemini IV, IX-A, X, XI, XII, and the Apollo 9 flights. Transearth EVA (returning from the moon) was performed on Apollo 15 and 16. Missions involving lunar surface EVA include the Apollo 11, 12, 14, 15 and 16 flights. Apollo 17 is scheduled for both lunar and transearth EVA. No interplanetary missions have been conducted. Presented below are brief descriptions of the Gemini and Apollo programs' EVA objectives and accomplishments and a listing of the overall conclusions derived from the EVA experience (refs. 1.3 and 1.4).

1.3.1 Gemini Program

The initial U.S. step into EV space was taken on the second manned Gemini flight, GT-IV (see Figure 1-1). By the end of the Gemini Program, five EVAs were completed totaling 6:01 hours of tethered EVA and an additional 6:24 hours of EVA standing in the open hatch. The primary EVA objectives of the Gemini Program were to:

- Develop the capability to perform EVA.

- Use EVA to increase the basic operational capability of the spacecraft.

- Develop operational techniques and evaluate advanced equipment in support of EVA for future programs.

These objectives were met with varying degrees of success through the following accomplishments:

- Completion of short-duration EVA, thus establishing EVA feasibility

- Evaluation of basic EVA equipment (e.g., tools)

- Evaluation of various maneuvering units

- Evaluation of several life support systems

- Retrieval of several experimental packages

FIGURE 1-1: Astronaut Edward White Evaluating the Hand Held Maneuvering Unit (HHMU) During America's First EVA Mission--Gemini IV.

- Conduct of photographic experiments
- Manual support of vehicle docking
- Evaluation of body restraint systems
- Evaluation of translation systems
- Conduct of camera maintenance

During the Gemini Program, the early missions were primarily concerned with an evaluation of various maneuvering units (see Table 1-1). However, because of problems (such as excessive workloads) encountered by the astronauts, the emphasis was shifted to an extensive development and evaluation of body restraint equipment. Detailed results of the Gemini EVAs are documented in NASA SP-149, Summary of Gemini Extravehicular Activity, and NASA SP-138, Gemini Summary Conference.

1.3.2 Apollo Program

Thus far, the Apollo Program has encompassed orbital, transearth, and lunar EVA. Although the emphasis of this document is on orbital EVA, lunar EVA experience is presented here because of the close similarities of orbital and lunar EVA equipment, operation, and environment. Beginning with Apollo 9 and continuing through Apollo 16, approximately 2 hrs. of orbital (including transearth) EVA and 59 hrs. 24 mins. of lunar EVA have been logged (hatch opening to hatch closing).

- ORBITAL and TRANSEARTH EVA was conducted only during the Apollo 9, 15 and 16 missions. Several of the Gemini EVA contributions used in planning the Apollo EVAs included the following:

    - Use of underwater simulation of EVA tasks to develop "real" timelines with adequate rest periods to reduce excessive workloads.
    - Reinforcement of the recognized need for Liquid Cooling Garments (LCG) to aid in the maintenance of body temperature.
    - The addition of adequate astronaut restraint devices.

  The primary objectives of the Apollo Orbital EVAs (refs. 1.5 and 1.8) were to:

    - Demonstrate the capability for extravehicular transfer from the lunar module to the command module (this capability is required as a backup to the nominal intravehicular transfer).
    - Demonstrate the operational adequacy of the Apollo A-7L EVA suit, life support equipment, and procedures in support of subsequent lunar landing missions (see Figure 1-2).

TABLE 1-1: Summary of Gemini Extravehicular Activity Statistics

Gemini Mission	Life Support	Umbilical Length (Feet)	Maneuvering Device	Umbilical EVA Time, hr:min	Standup Time, hr:min	EVA Time, hr:min
IV	VCM[1]	25	HHMU	0:36	None	0:36
VIII	ELSS,ESP	25	HHMU	None	None	None
IX-A	ELSS,AMU[2]	25	AMU	2:07	None	2:07
X	ELSS	50	HHMU	0:39	0:50	1:29
XI	ELSS	30	HHMU	0:33	2:10	2:43
XII	ELSS	25	None	2:06	3:24	5:30
Totals for Gemini Program				6:01	6:24	12:25

- Retrieve panoramic and mapping camera film cassettes from the Scientific Instrument Module located on the Command Service Module.

The extravehicular operation also served to support other developmental objectives. These include photography of the exterior of both vehicles and the retrieval of thermal samples. Although the scheduled Apollo 9 EVA was shortened by 1:35 hours, all objectives were successfully accomplished (ref. 1.5).

The guidelines for the planning, the performance, and the desired results of EVA during the Gemini Program were proven and remained valid. A detailed discussion of the Apollo 9 flight is given in the Apollo 9 Mission Report, MSC-S-67-793.

---

[1]VCM - Ventilation Control Module
ELSS - Extravehicular Life Support System
AMU - Astronaut Maneuvering Unit
ESP - Extravehicular Support Package
HHMU - Hand Held Maneuvering Unit

[2]The AMU was not evaluated on Gemini IX-A due to inadequate restraint systems and helmet visor fogging.

FIGURE 1-2: Astronaut Russell Schweickart Evaluating the Portable Life Support System (PLSS) During Apollo 9 EVA

- LUNAR EVA was conducted during the Apollo 11, 12, 14, and 15 missions. The prime objectives of these "two-man-EVAs" (ref. 1.6) were:

  - To place an American on the moon.

  - To obtain a greater understanding of man's capabilities and limitations.

  - To conduct extensive geological explorations as a means of determining the origin of the moon and earth.

  - To find uses for the moon as an in-orbit platform around the earth.

  - To prove that man can perform complex tasks, without undue difficulty, as an efficient scientific explorer in an alien environment (see Figure 1-3).

The following accomplishments have been recorded during lunar missions (through Apollo 16) as a means of achieving the program objectives:

- Approximately 635 pounds of lunar material samples have been collected from the various landing sites and returned to earth.

- Seismic, solar wind, heat flow, magnetic field, lunar gravity, suprathermal ion detector, cold cathode ion gauge, lunar core drilling, and laser retro-reflector experiments have been conducted.

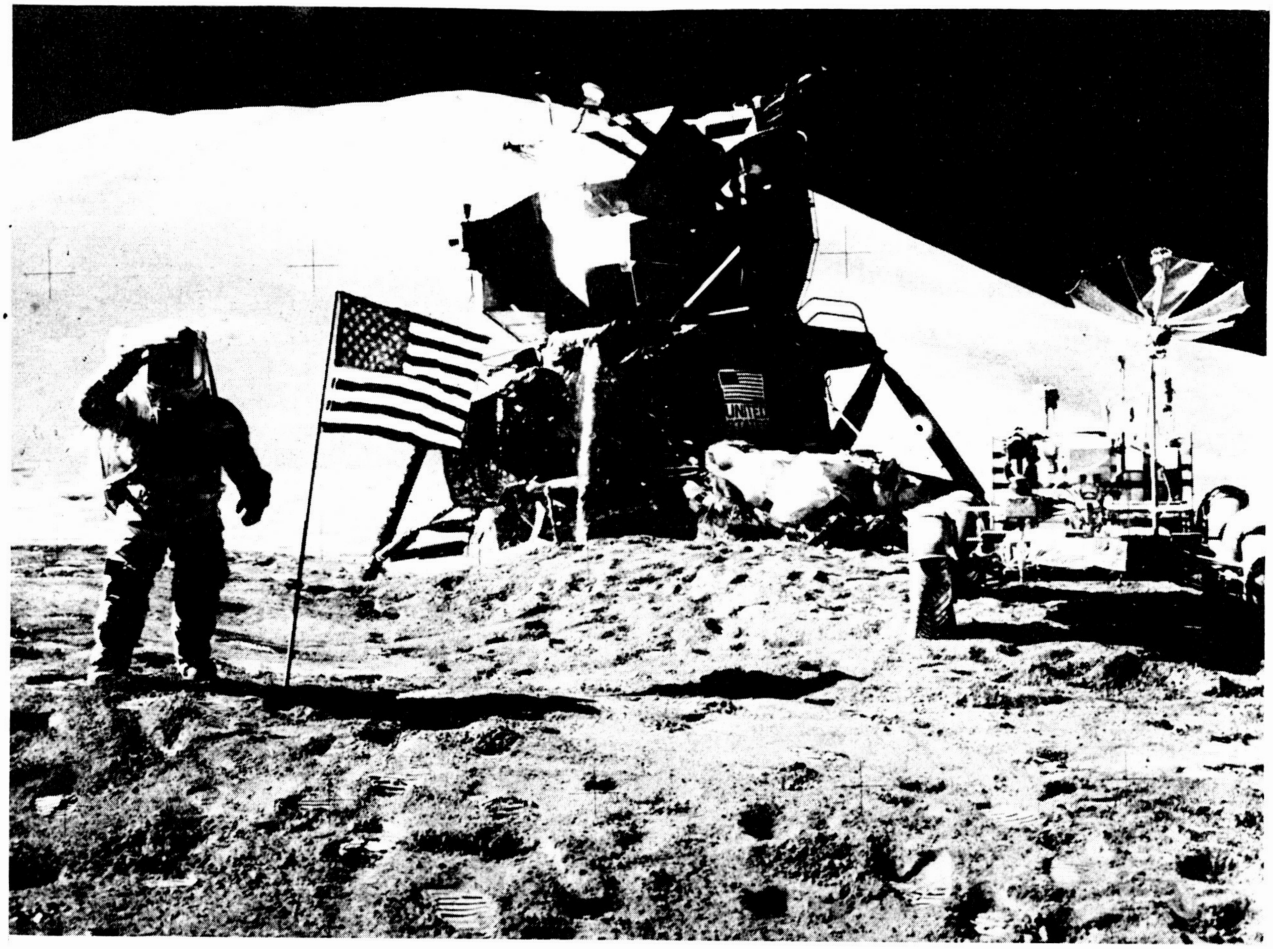


FIGURE 1-3: Astronaut James Irwin with Lunar Module and Lunar Roving Vehicle - Apollo 15

- Numerous lunar miles have been traversed and photographed by the astronauts.
- Several geophysical phenomena have been better identified.
- Several articles from the Surveyor 3 have been collected in order to determine the effects of the lunar environment over a precisely known time period.
- Numerous high quality photographs have been taken.

The outstanding success of the lunar EVAs and the many benefits gained for the extent of effort involved has prompted a more ambitious set of EVA plans for subsequent Apollo lunar surface missions. Detailed discussions on each of the Apollo lunar EVAs are contained in respective mission reports. A summary of the Apollo missions is shown in Table 1-2 (refs. 1.5, 1.7 through 1.9).

TABLE 1-2: Summary of Apollo Extravehicular Activity

Apollo Mission	Subgroup	Landing Site	Number of EVAs	Total Time for EVA (hrs : mins)	EVA Man-hours	Rock Samples Collected (approx. lbs.)
9	Orbital	N/A	1	0:46	1:32	N/A
11	Lunar	Sea of Tranquility	1	2:32	5:04	50
12	Lunar	Surveyor Crater	2	7:43	15:26	120
14	Lunar	Fra Mauro	2	9:25	18:50	80
15	Standup	Hadley Rille	1	0:33	1:06	N/A
15	Lunar	Hadley Rille Area	3	19:46	39:32	171
15	Transearth	N/A	1	0:38	1:54	N/A
16	Transearth	N/A	1	≈1:00	≈1:00	≈215
Totals for Apollo Program			12	≈42:23	≈84:24	≈626

1.3.3 Conclusions Derived from EVA Experiences

By the close of the Gemini Program, results of the EVA experiences had prompted the following conclusions and recommendations as a foundation for the development of future EVA systems (refs. 1.3 and 1.4).

- EVA can be used for productive tasks.
- In the development of EVA systems, attention should be given to the following:
  - mobility aids (handholds, handrails)
  - body restraints (tethers, foot restraints)
  - task sequence
  - workload control and human performance limits
  - realistic simulation and proper training

- thorough mission monitoring
- life support equipment operation limits

- Space suit mobility is a limiting factor in the EVA tasks which can be accomplished. Development efforts need to be directed toward improved mobility.
- Water immersion facilities provide a high fidelity simulation of orbital EVA weightlessness and are effective for procedures development and crew training.
- Vacuum chamber training, with the EVA crewmen using their flight space suits and extravehicular life support equipment, contributed significantly to the readiness of crews to perform actual EVA.
- Loose equipment should be restrained at all times during orbital EVA to prevent loss.
- Restraint systems should be developed that will provide a greater degree of freedom for the astronaut during orbital EVA.
- Evaluations of maneuvering units as a means of orbital EVA transportation should be continued. Evaluations to date have been too brief to fully define the units' capabilities and limitations.

1.4 SURVEY OF APPROVED EXTRAVEHICULAR FLIGHT ACTIVITIES

At present, EVA has been selected as a primary operational technique in the remaining Apollo and future Skylab Programs. The following is a brief description of the proposed tasks/objectives to be accomplished in each of the programs.

1.4.1 Apollo Program

One Apollo mission (Apollo 17) currently comprises the remainder of the Apollo Program. The mission is tentatively planned to include three lunar EVAs and one transearth EVA. Each of the lunar EVAs is scheduled to last six to seven hours and the transearth EVA approximately 70 minutes. The overall program objectives for this lunar mission are as follows:

- to perform selenological inspection, survey, and sampling of materials and surface features in preselected areas (ref. 1.9)
- to deploy and activate surface experiments (ref. 1.9)
  - S-031 Passive Seismic
  - S-033 Active Seismic
  - S-034 Lunar Surface Magnetometer
  - S-037 Heat Flow
  - S-059 Lunar Gravity Investigation

- S-152 Cosmic Ray Detector
- S-198 Lunar Portable Manetometer
- S-199 Lunar Gravity Traverse
- S-200 Soil Mechanics
- S-201 Far UV Camera/Spectroscope
- S-202 Lunar Ejecta and Meteorites
- S-203 Lunar Seismic Profiling
- S-204 Surface Electrical Properties
- S-205 Lunar Atmospheric Composition
- S-207 Lunar Surface Gravimeter

- to evaluate the capability of the Apollo equipment to provide extended lunar surface stay time, increased EVA operations, and surface mobility (ref. 1.9)

- to conduct extensive photographic and video coverage (ref. 1.9)

Two of the primary objectives of the Apollo 16 and 17 EVAs were identical to those conducted on the Apollo 15 mission. Additional EVA operations were scheduled. The Apollo 16 and 17 transearth EVA opeations are listed below:

- Retrieval of a 24 inch focal length panoramic camera cassette

- Retrieval of a 3 inch focal length metric camera cassette

- Conduct of a microbial response experiment using a self-contained Microbial Environment Exposure Device - MEED (Apollo 16 only)

1.4.2 Skylab Program

The Skylab Program is the only presently approved system development activity which will use orbital EVA (see Figure 1-4). One primary objective of this program is the acquisition of photographic data on solar activity. This objective will be accomplished through the use of the Apollo Telescope mount (ATM), which is a canister (part of the Skylab Cluster) containing several telescopes and film magazines. The orbital EVA support for the ATM will consist of one astronaut translating between an Airlock Module (AM) and two workstations on the ATM, removing and replacing six film magazines, and returning the exposed film magazines to the AM. A second EVA astronaut will be stationed outside the AM to support the film retrieving astronaut, manage his umbilical, and assist him if necessary. In all, six EVA excursions will be performed, each lasting about two and one-half hours. A summary of the Skylab EVA mission operations is presented in Chapter II, Section 2.2.

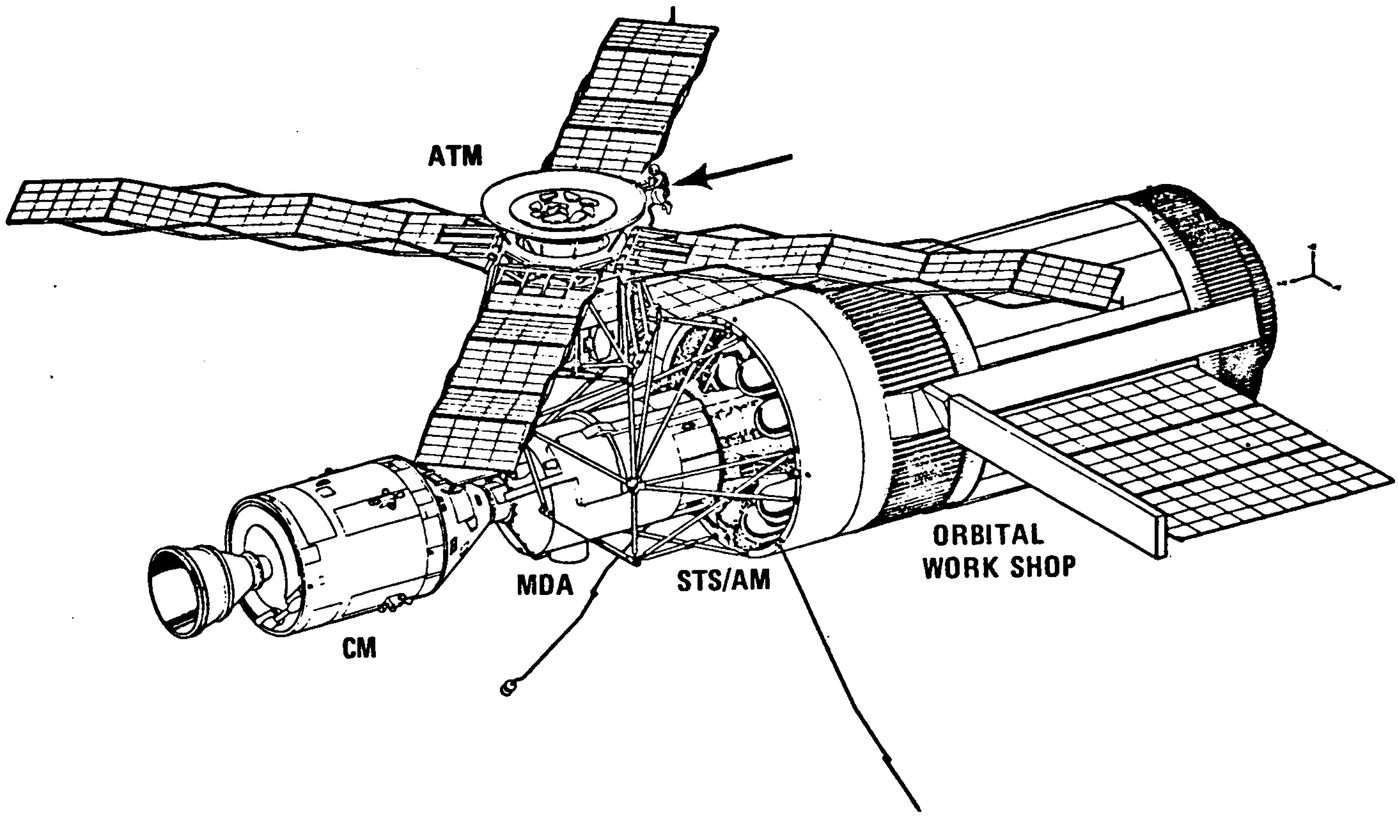


FIGURE 1-4: The Skylab Cluster, Showing the EVA Crewman (arrow) Ingressing the Sun End Workstation on the ATM

1.5 ALTERNATIVES TO MANNED EXTRAVEHICULAR ACTIVITIES

In 1967, the Surveyor III spacecraft touched down on the lunar surface, carrying with it a mechanical surface sampler system, which performed a variety of operations on the surface. This was two years before the arrival of man, aboard Apollo 11, to perform sampling tasks.

This historical note points out the two prime methods of performing activity in an extraterrestrial environment (or in space) -- namely, manned and unmanned. The unmanned method is presently designated as that using remote manipulators and automatic systems. Remote manipulators range in system complexity from the simple, special-purpose, nondexterous "hand" type used on Surveyor III to those which are of the highly sophisticated, multipurpose, adaptive type being proposed for the rendezvous and capture missions of orbiting satellites. They find application in operations where man needs to extend, project, or multiply his manipulatory capability.

The man/manipulator tradeoff methodology is not considered within the scope of this document, and since this subject has received adequate attention in other relevant NASA documentation (refs. 1.10 and 1.11), further discussion of remote manipulators and their applicability to EVA will not be included.

1.6 PROJECTED APPLICATIONS FOR EVA

In any manned scientific or exploratory space mission, a backup EVA capability must be provided and must remain intact even if all other systems have failed. Therefore, a continued development of EVA capabilities is essential to all future manned space programs. In addition to meeting contingency EVA requirements, planned utilization of manned EVA is identified on future orbital space missions and includes exploration, inspection, retrieval of data modules, extraterrestrial sample collection, assembly of structures, servicing, repair and resupply. Worthy to note is the flexibility inherent in manned EVA for the performance of a broad range of functions.

In addition to the EVA to be performed on the remaining Apollo flights and the Skylab Program, tentative requirements for EVA have been defined in the Modular Space Station, Space Shuttle, Research and Application Module (RAM) and other preliminary documentation (refs. 1.4 through 1.13) concerning future space missions planning. These requirements cover such areas as test apparatus and test sample installation, retrieval of experiment equipment and data, repair and maintenance, emergency rescue provision, backup access to RAM and payload modules, and EVA equipment development and evaluation tests (refs. 1.12, 1.14, and 1.15). Additional information concerning EVA task applications on future orbital missions is contained in Chapter II, Section 2.4.

REFERENCES

1.1 NASA: NASA Management Instruction (NMI), 1152.36B, September 30, 1969.

1.2 NASA: Compendium of Human Responses to the Aerospace Environment, Vols. I, II, and III, NASA-CR-1205, Lovelace Foundation for Medical Education and Research, 1968.

1.3 NASA: Summary of Gemini Extravehicular Activity, NASA-SP-149, Washington, D.C., 1967.

1.4 NASA: Gemini Summary Conference, NASA-SP-138, Washington, D.C., 1967.

1.5 Manned Spacecraft Center: Apollo 9 Mission Report, MSC-S-67-763, Houston, Tex., May 1969.

1.6 Naugle, John E. (NASA's Associate Administrator for Space Science and Applications). Information furnished to a subcommittee of the Committee of Appropriations, House of Representatives, 91st Congress, March 24, 1970.

1.7 Manned Spacecraft Center: Apollo 15 Preliminary Lunar Surface Procedures, Houston, Tex., April 30, 1971.

1.8 Apollo 15 Mission (AS-510) Post Launch Mission Operation Report No. 1, No. M-933-71-15, August 16, 1971.

1.9 Manned Spacecraft Center: Apollo Spacecraft Program Plan (Lunar Exploration Missions), MSC-02538, Rev. 4, 1971.

1.10 Matrix Research Co.: Selection of Systems to Perform Extravehicular Activities -- Man and Manipulator, Contract No. NAS8-24384, Huntsville, Ala., 1969.

1.11 NASA: A Descriptive Model for Determining Optional Human Performance in Systems, Vol. III, NASA-CR-878, 1969.

1.12 NASA: Reference Earth Orbital Research and Applications Investigations (Blue Book), NHB 7150.1, January 15, 1971.

1.13 Martin Marietta Corp.: Experiment Requirements Summary for Modular Space Station and Space Shuttle Orbital Applications and Requirements, Rev. 1, Subcontract Nos. MDAC-WO-69-4-016 and MDAC-W-71-1-001, 1971, Martin Marietta Denver Div., 1971.

1.14 General Dynamics: Research and Applications Module (RAM), Phase B Study, Contract NAS8-27539, August 28, 1971.

1.15 Martin Marietta Corp.: Experiment Requirements Summary for Modular Space Station and Shuttle Orbital Applications and Requirements, Rev. 1, Subcontract No. MDAC-WD-69-4-016, April 28, 1971.

CHAPTER II

ORBITAL EVA APPLICATIONS

TABLE OF CONTENTS

2.0 INTRODUCTION

One of the many basic design decisions concerning future orbital missions will be whether to employ manned EVA to accomplish tasks external to the spacecraft or to use mechanical Remote Manipulator Systems (ROMANS) and/or automated systems. The decision will be based on factors such as weight penalty, complexity, operational characteristics, safety, cost, and the technology status of remote and manned systems. In order to provide a baseline from which future EVA programs can be planned and developed, the present level of manned EVA technology must be known to the mission planners and designers. The objective of this chapter is to provide an overview of the orbital EVA operations performed on the Gemini and Apollo (through Apollo 16) programs and those planned for Skylab. The type of EVA tasks performed on previous missions and the supporting hardware (excluding space suits and life support systems) are briefly discussed.

The chapter also includes the following: a summary of EVA functions and tasks derived from an assessment of the operations performed during previous orbital EVA missions; a classification and description of EVA functions; the results of a survey conducted to determine candidate EVA task applications on future space missions; and a listing of the major EVA systems design/selection considerations that must be acknowledged in planning for manned EVA on future orbital space programs.

Chapter II stresses the fact that manned EVA is an accepted means of accomplishing external tasks and should be utilized where tradeoff studies show that performance of a certain task can best be done by man. The data contained in the chapter, combined with that in the succeeding chapter, provide information necessary in making an accurate determination of the present level of EVA technology and identification of areas requiring additional research and development.

2.1 HISTORICAL APPLICATIONS

The studies conducted to evaluate the role of man in future orbital space missions, the selection of either a man or a machine to perform EVA work functions, and the decision to use existing EVA support systems or systems now being developed must all be made in the light of related extravehicular activities performed on past missions and also those activities which are planned for present and future missions.

When considering the support systems required by man during orbital EVA, a thorough analysis of previous EVA applications is necessary in order to compare future EVA task functions and man/system capabilities. Experience gained from the Gemini and Apollo extravehicular operations has provided much useful information in planning for future EVAs, particularly for Skylab. Each Gemini and Apollo flight relied heavily on the experience derived from

previous flights. Through this experience, it was confirmed that work tasks, equipment, and timelines can be tailored so that manned EVA objectives can be accomplished. A review of the orbital EVA tasks performed, the equipment used, and the results of equipment performance are discussed to aid the EVA mission planner. The astronaut life support and protective systems will be discussed in later chapters.

2.1.1 Gemini EVA

The earlier Gemini EVA mission objectives were concerned with establishing the feasibility of EVA, evaluation of Astronaut Maneuvering Units (AMU), retrieval of micrometeorite data packages, and the evaluation of extravehicular life support systems. The later Gemini EVA missions were primarily directed toward the evaluating of body restraints, mobility aids, and body attitude control during translation. Other tasks accomplished included photography, contamination and thermal sample retrieval, cargo transfer (film magazines), and translation rail evaluation.

Since the feasibility of manned EVA was established early in the Gemini Program, the areas of major concern, in view of future applicability, on both the Gemini and Apollo EVA operations were: (1) crew protective and life support systems (discussed in Chapter III); (2) extravehicular maneuvering equipment; and (3) equipment used to provide body positioning, stabilization and restraint during translation or task performance activities.

2.1.1.1 Extravehicular Maneuvering Equipment

Initial plans for the use of extravehicular maneuvering equipment were aimed at evaluating the Hand Held Maneuvering Units (HHMU) during the Gemini IV, VIII, X and XI missions, and evaluating the Air Force Astronaut Maneuvering Unit (AMU) during the Gemini IX-A and XII missions. The evaluations of the HHMU planned for Gemini VII, X, and XI, and the AMU on Gemini IX were not completed due to other equipment problems. The AMU was not carried on Gemini XII because of the increased emphasis on the evaluation of restraint systems for body control and task performance. The HHMU was the only maneuvering unit evaluated on orbit, and only limited experience and data were gained.

The HHMU was first evaluated on Gemini IV. Controlled maneuvers involving linear translation, pitch, yaw, and various combinations of maneuvers were successfully conducted without disorientation. The HHMU evaluation did not include transfer and docking at a specific target. Only a small amount of data was obtained on maneuvering velocity, precision, and propellant use rates. The HHMU used during Gemini IV EVA is shown in Figure 2-1. A modified HHMU was used with limited success on Gemini X to transfer from the Gemini spacecraft to a nearby (approx. 10 ft.) Agena spacecraft to retrieve an experimental package (see Figure 2-2). The feasibility of the HHMU as a translation aid was established during the brief evaluations; however, recommendations were made to further evaluate the unit in orbital flight, with emphasis on stability and control capabilities (ref. 2.1).

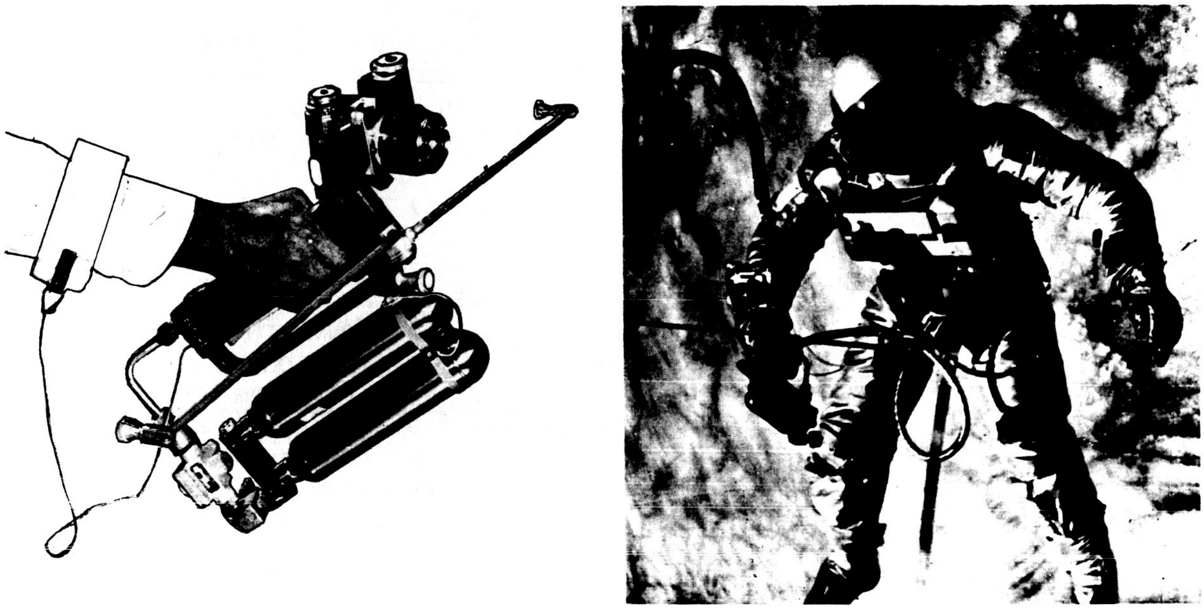


FIGURE 2-1: Gemini IV Hand Held Maneuvering Unit Configuration and Orbital Evaluation

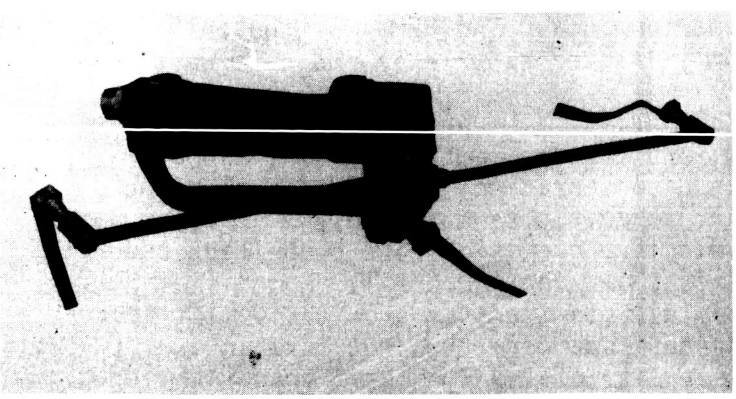


FIGURE 2-2: Gemini X Hand Held Maneuvering Unit Configuration

The Astronaut Maneuvering Unit, Figure 2-3, is a compact backpack mechanism which contains the necessary systems to permit an extravehicular astronaut to maneuver in space independent of spacecraft support. Evaluation of the AMU was not accomplished as scheduled on Gemini IX-A due to severe helmet visor fogging during the AMU preparation activities.

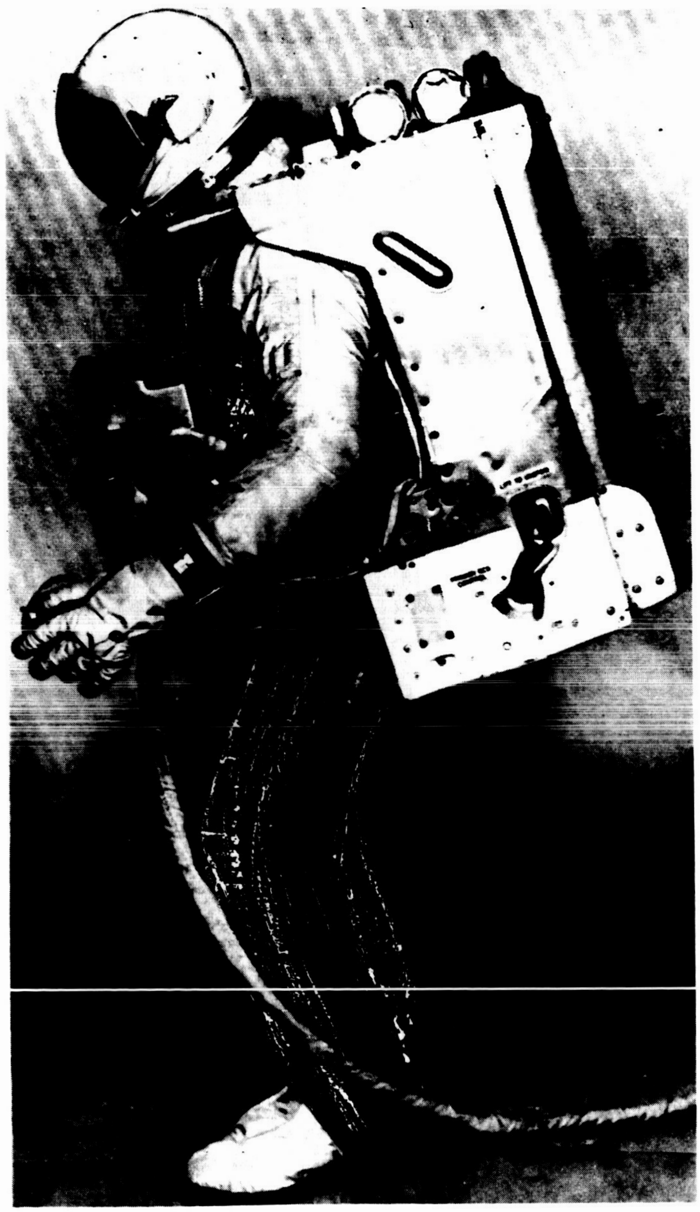


FIGURE 2-3: Air Force Astronaut Maneuvering Unit Configured for Gemini IX-A

Although the AMU orbital evaluation was not accomplished, useful data was obtained from the design, development, testing and training program in preparation for the evaluation. A modified version of the AMU is scheduled for critical review (inside the Orbital Workshop) on Skylab, and it is presently being considered for use on future space stations and on Space Shuttle missions. The physical and performance characteristics of the AMU and HHMU are presented in Chapter III.

2.1.1.2 EVA Restraint Systems

One of the more striking conclusions derived from early Gemini EVA experience was that man's capability to perform useful functions outside the spacecraft was drastically reduced without suitable restraint provisions. The necessity of body restraints during EVA was shown on Gemini IV. After completing the HHMU evaluations, the astronaut evaluated the umbilical as an aid in body positioning and in translating in space. It was concluded that the umbilical was useful only as an aid in moving to its origin and that more rigid handholds would be required for other EVA operations. The importance of the requirement was confirmed when restraint problems contributed to the premature termination of the Gemini IX-A and XI extravehicular operations. The Gemini XII EVA mission verified that, with an adequate restraint system, man can perform a number of moderately complex tasks in the extravehicular environment. To stress the importance of restraint systems for performance of EVA functions, forty-four pieces of equipment were provided on the later Gemini XII mission for extravehicular body restraint, in contrast to nine pieces of restraint equipment for Gemini IX-A EVA (ref. 2.2).

The first major task attempted during Gemini EVA was the checkout and donning of the AMU on Gemini IX-A. A pair of foot restraints was provided for performing the tasks. The attempts to perform two-handed tasks were exceedingly difficult, since work had to be terminated every few seconds to regain body position. The foot restraints were considerably less useful when bending forward or applying a downward force. This movement created a corresponding movement which forced the feet out of the restraint system. Postflight analysis of the restraint problems resulted in the development of new foot restraints (Figure 2-4) for the Gemini XI and XII EVA operations. Molded fiberglass foot restraints (dutch shoes), custom fitted to the astronaut's boots, were found adequate for all tasks utilizing foot restraints on Gemini XI and XII. Similar foot restraints were satisfactorily used during Apollo 9 extravehicular operations on the Lunar Module forward platform.

Several handhold, handrail, and tether device configurations were evaluated during the Gemini Program to aid in maintaining body position during task performance and during translation. The restraint devices evaluated for EVA operations on the Gemini Program are summarized in Table 2-1 (ref. 2.2). Rectangular handrails and handholds (1.25 in. by .55 in.) were preferred for travel between two points on the spacecraft surface. The rectangular cross section offered more resistance to rotation than the cylindrical handrail for a given hand force and allowed better control of body attitude during translation.

FIGURE 2-4: EVA Foot Restraints Used on Late Gemini and Apollo Programs

Cylindrical handrails of large (1.38 in.) diameter were satisfactorily used to ingress foot restraint systems and to perform tether evaluation exercises. Small cylindrical handrails (0.317 in. dia.) were flown but were not extensively evaluated. The configuration was usable as a handhold, and it permitted direct attachment of the waist tethers. The larger diameter handrail was the most preferred of the cylindrical handrails evaluated.

A telescoping handrail was used to travel from the spacecraft hatch to the nose of the spacecraft on Gemini XII. The handrail was manually extended, and the small end was secured in a special receptacle on the target-vehicle docking cone. The large end was secured on the spacecraft center beam between the hatches. The handrail was adequate for translation purposes; however, its nonrigidity was considered inappropriate and did not provide absolute control of body position and attitude when the handrail flexed. Rigidly mounted rectangular handrails generally proved to be the most desirable for EVA translation operations.

TABLE 2-1: EVA Restraint Systems Used on the Gemini Program

Restraint System Configuration	Gemini Mission			
	IX-A	X	XI	XII
Rectangular handrail	X	X	X	X
Large cylindrical handrail (1.38 in. dia)	X			X
Small cylindrical handrail (0.317 in. dia)				X
Telescoping handrail				X
Fixed handhold			X	X
Rigid Velcro-backed portable handhold				X
Flexible Velcro-backed portable handhold	X			
Waist tethers				X
Pip-pin handhold/tether-attach device				X
Pip-pin antirotation device				X
U-bolt handhold/tether-attach device				X
Foot restraints	X			X
Standup tether		X	X	X
Straps on space-suit leg			X	X

Portable, flexible handholds with Velcro backing were evaluated as restraints and mobility aids during the Gemini IX-A EVA mission. The handholds were attached to the EVA crewman's gloves with an elastic strap, and approximately 80 patches of nylon Velcro hook were attached to the spacecraft surface to engage the pile handholds. The flexible handholds were considered inadequate due to the following: (1) the contact forces were not sufficient to permit controlled maneuvering or control of body attitude (although they were adequate for station keeping); (2) the elastic glove attachments were not adequate since one became detached during EVA evaluation; and (3) the Velcro hook on the spacecraft nose was degraded by launch heating.

Another Velcro-backed portable handhold concept was prepared for evaluation on Gemini XII. One set of rigid handholds having approximately nine square inches of nylon-pile Velcro and another set having about sixteen square inches of polyester-pile Velcro were developed. Ground based simulations prior to the Gemini XII flight indicated a number of limitations concerning the usefulness of the units. As a result of these simulations, detailed evaluations of the rigid Velcro-backed portable handholds were not included in the flight plan for Gemini XII EVA. One prominent disadvantage of Velcro is that it works best when placed in shear rather than tension. This limits

its usefulness, especially for handholds. Also, for a handhold, its restraining force should be much greater than the force required to apply the Velcro, which was not the general condition, particularly with the nylon Velcro.

Waist tethers were evaluated on Gemini XII as a prime body restraint system (Figure 2-5). The tethers were fabricated of relatively stiff nylon webbing with a length-adjustment buckle and a hook for connecting the tether-attach rings. The tethers were attached to the space suit slightly below waist level. During the EVA tether evaluation exercises, several tether-attach points were used on the spacecraft adapter section and the target vehicle. Using only the waist tethering system, the EVA crewman could install and torque bolts to approximately 200 in.-lbs. with a conventional torque wrench.

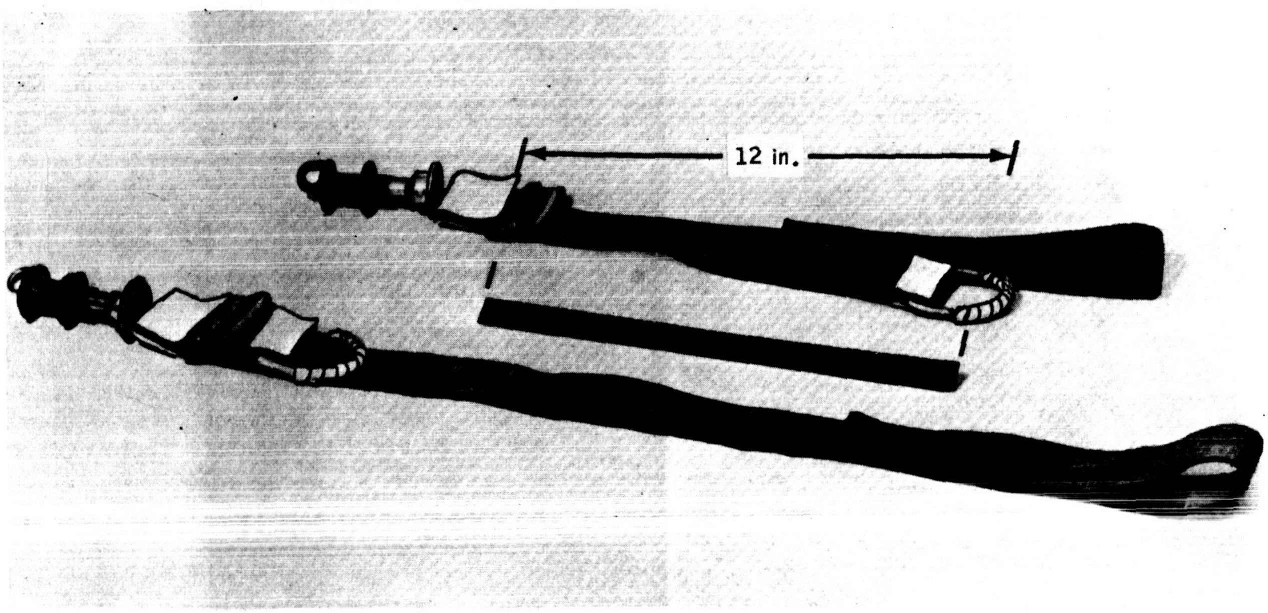


FIGURE 2-5: Waist Tethers Used on Gemini XII

Several other tasks were performed on Gemini XII to evaluate the usefulness of the tether restraint system. These tasks included removing and replacing Velcro pads, connecting and disconnecting electrical and fluid connectors, activating micrometeorite collection experiments, and performing a variety of tether hook and ring connection exercises. From the Gemini XII evaluations, it was determined that tethers were beneficial in controlling body position, eliminating the possibility of losing equipment in space, and providing necessary restraint for performing push, pull and torquing operations of relatively high magnitude.

A number of combination pip-pin handhold and tether devices (Figure 2-6) were evaluated during the Gemini XII EVA mission. The conventional ball detent pip-pin mechanism was used for attaching the unit to the spacecraft.

A tee handle and D-ring were incorporated into the body of the device to facilitate their use as handhold and tether attachments. The pip-pin devices were evaluated using a standard receptacle, which allowed the unit to rotate 360°, and an antirotation receptacle, which restrained the unit in one of eight positions. The units were evaluated as aids during changes in body position, during their utilization as waist tether-attach points, and during the performance of various work tasks on the target vehicle. The pip-pin units were considered more valuable in the antirotation configuration, but the requirements for precise alignment in attaching the units to the spacecraft receptacles was undesirable.

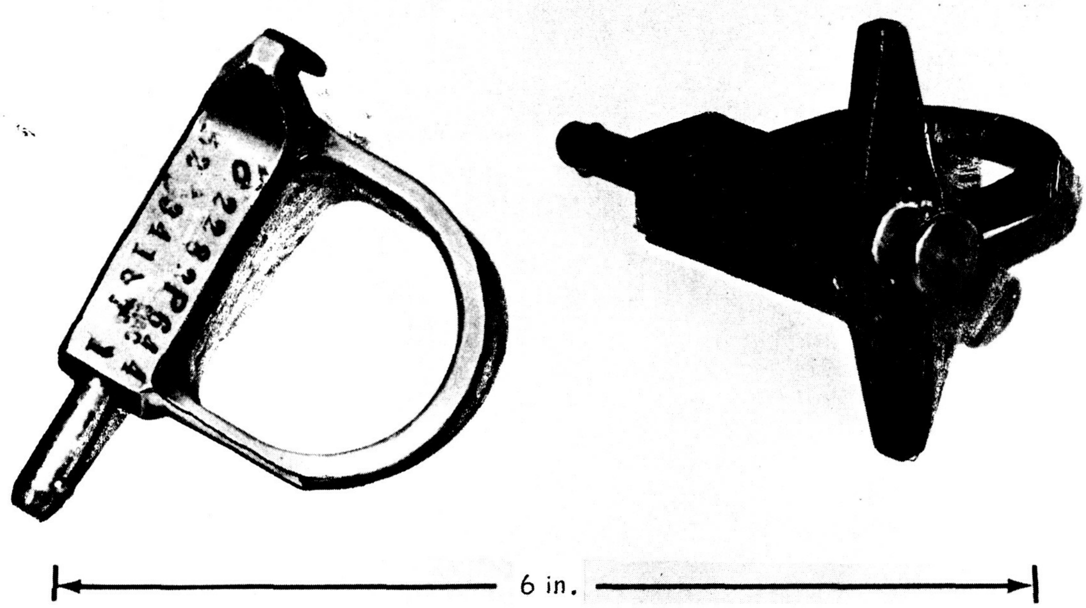


FIGURE 2-6: Pip-Pin Combination Handhold and Tether Attachment

Several U-bolt units were included in the Gemini XII EVA body restraint evaluation package. The EVA crewman found the U-bolts useful as auxiliary handholds during work task performance and during body position changes. The units were most useful as waist tether attachments.

The molded foot restraints (dutch shoes, shown in Figure 2-4) were considered by the EVA crewman to be far superior to all restraint devices evaluated on the Gemini Program. With properly sized foot restraints, the EVA crewman was able to perform orbital tasks comparable to those in 1-g ground based simulations. Torquing operations in excess of 200 in.-lbs., cutting operations, and connector alignment tasks were easily accomplished. The body attitude constraint characteristics of the foot restraints were also evaluated. The crewman was able to force himself backward approximately 90°, roll ±45° and yaw almost ±90°.

Standup tethers and space suit leg straps were also provided on several of the Gemini missions. The tethers were used to restrain the EVA crewman during open hatch standup activities on the Gemini X, XI and XII missions. The leg strap restraint was attached to the space suit left leg calf area and was handheld by another crewman. The strap was intended to serve in the same capacity as the standup tether but was not used since it was easier for the second astronaut to hold the foot.

2.1.1.3 Orbital EVA Capability Conclusions

The Gemini EVA missions demonstrated the basic techniques required for the productive use of man to perform functions outside the spacecraft. Extravehicular functions in the space environment are feasible and useful for productive tasks if adequate attention is given to body restraints, task performance sequence, workload rate control realistic simulations for technique development, and proper ground based training. A summary of the orbital EVA functions performed on the Gemini and the Apollo (9, 15 and 16) flights is outlined in Table 2-2. The Apollo 16 EVA functions were identical to Apollo 15, with the exception of the MEED experiment noted in Chapter I. Problem areas were sufficiently defined to indicate the preferred and required support equipment and operational procedures for general extravehicular operations in future space programs. The need for mobility aids for translation over the exterior surface of the space vehicle was shown. The requirements for body restraints were established and the capabilities of foot restraints and tethers were demonstrated. Several methods for crewman transfer between orbital space vehicles were evaluated, and the feasibility of extravehicular operations on the night side of the orbit was confirmed. The capability to perform tasks of varying complexity was also demonstrated, and some of the factors that limit task complexity and performance difficulty were identified.

2.1.2 Apollo Orbital EVA

Prior to the Apollo 11 lunar landing, development of hardware and procedures for extravehicular transfer from the lunar module to the command module (in the event that the transfer tunnel became impassable) was required. This planned extravehicular operation on Apollo 9 provided the opportunity to support other developmental objectives, such as portable life support systems, photography, thermal sample retrieval, handrail evaluation, and body control during translation (Figure 2-7 and 2-8). The official EVA timeline specified that the Lunar Module Pilot would egress the lunar module, transfer to the open hatch in the command module, and then return to the lunar module. The initial plan, however, was abbreviated due to the crowded timeline required for rendezvous the following day and a minor inflight illness experienced by one of the crewmen on the day prior to the scheduled EVA operation objectives.

The PLSS was successfully donned, and checkout operations were completed. Egress hatch operations were evaluated, and thermal samples were easily retrieved from the command module using the restraint and handrail systems provided. Body control by means of the Gemini dutch shoes and the rectangular

TABLE 2-2: EVA Functions on Past Missions

OPERATION/TASK \ PAST MISSION	GEMINI IV	GEMINI IX A	GEMINI X	GEMINI XI	GEMINI XII	APOLLO 9	APOLLO 15
• Hand Held Maneuvering Unit (HHMU) evaluation	●		●				
• Install Umbilical Guard	●						
• Umbilical evaluation (tether Dynamics)	●	●	●				
• Photography (General/Stellar)	●	●	●	●	●	●	
• Handrail deployment/evaluation		●	●	●	●	●	●
• Velcro pad evaluation		●			●		
• Attachment of docking bar mirror		●					
• Camera installation (16mm)		●			●		
• Micrometeorite package retrieval (S012)		●	●				
• Unstowing of penlights		●			●		
• Translation (Crew/Cargo)		●			●	●	●
• Connection of tether hooks		●			●	●	●
• Astronaut Maneuvering Unit (AMU) preparation		●					
• Micrometeorite collection package retrieval (S010) from Gemini-Agena Target Vehicle (GATV)		●					
• Nitrogen quick disconnect operations		●					
• Experiment camera mounting - Ultraviolet Astronomics Camera (S013)			●	●	●		
• (External sequence camera) EVA camera mounting		●		●	●		

TABLE 2-2: EVA Functions on Past Missions (Cont'd.)

OPERATION/TASK \ PAST MISSION	GEMINI IV	GEMINI IX A	GEMINI X	GEMINI XI	GEMINI XII	APOLLO 9	APOLLO 15
• Retrieval of experiment (S009)				●			
• Film change				●	●		
• Attachment of spacecraft/GATV tether				●	●		
• Tether attachment evaluations					●		
• Retrieval of contamination sample disks					●		
• Cleaning command pilot's window					●		
• Evaluation of portable handholds					●		
• Operation of electrical and fluid quick disconnects					●		
• Evaluation of torquing operations					●		
• Evaluation of suit mobility					●		
• Evaluation of cutting tools					●		
• Activation of S010 and retrieval of sample package					●		
• Checkout and evaluation of the extravehicular mobility unit						●	
• Cabin depressurization function	●	●	●	●	●	●	●
• Crew translation and body attitude control evaluation						●	
• Retrieval of thermal samples from the service module						●	
• Film magazine retrieval							●

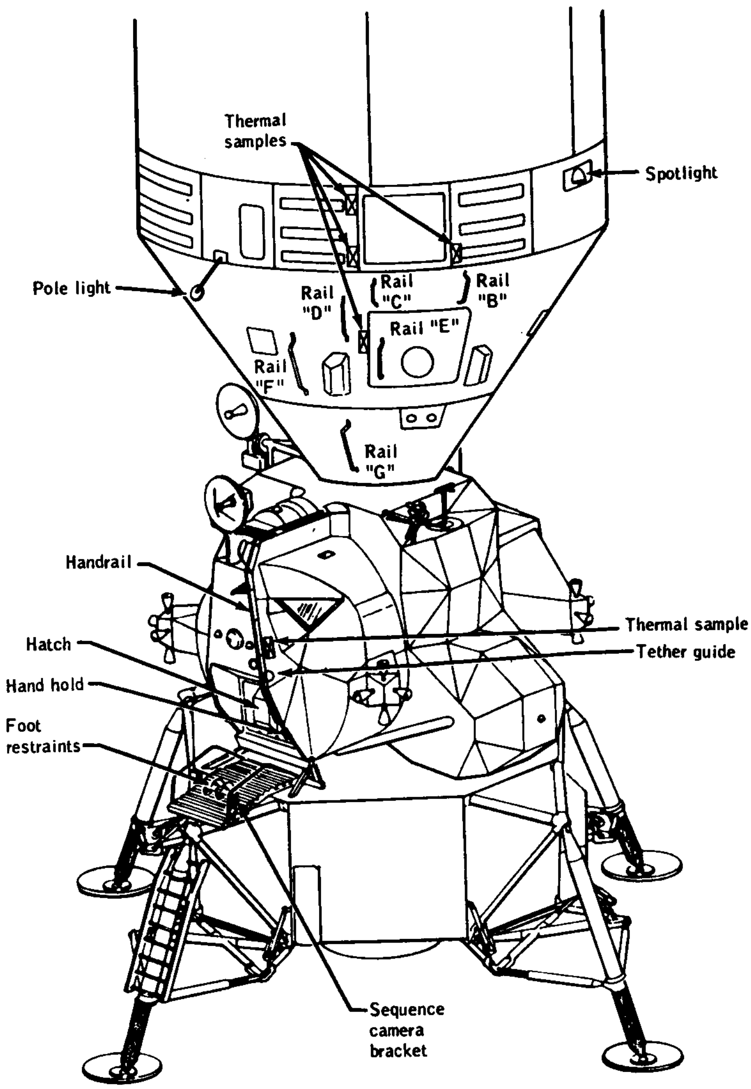


FIGURE 2-7: Apollo 9 EVA Restraint and Mobility Aid Location

handrail (1.25 in. by .62 in.) was considered by the EVA crewman to be excellent. All translation, hatch egress/ingress operations, and stability evaluations were performed satisfactorily with a minimum of effort. Some inflight task performance capabilities were found to be easier than they had been during reduced gravity ground based training exercises (ref. 2.3).

FIGURE 2-8: Handrail Evaluation During Apollo 9 EVA

An extravehicular lifeline (Figure 2-9) secured the crewman to the lunar module during all EVA operations. The lifeline was fabricated of Polybenzimidozale webbing one inch wide and 1/16 inch thick with an ultimate tensile strength of 600 pounds. Three hooks were provided, one permanently attached at each end of the lifeline and one that could be manually positioned to any point along the 25 foot tether length. The movable hook was to be used for transfer of camera and thermal samples. Each hook was provided with a locking device operated by the space-suited crewman.

The second crewman, performing standup EVA from the command module hatch, received life support from the spacecraft environmental control system umbilical. The umbilical also served as his restraint system during partial egress to retrieve thermal samples. A 14 foot thermal sample tether similiar to the EVA lifeline was provided. Two hooks were incorporated, one permanently attached to the end of the webbing and the other adjustable to any position along the tether length. The tether was designed to be used as an aid in closing the command module side hatch, if necessary.

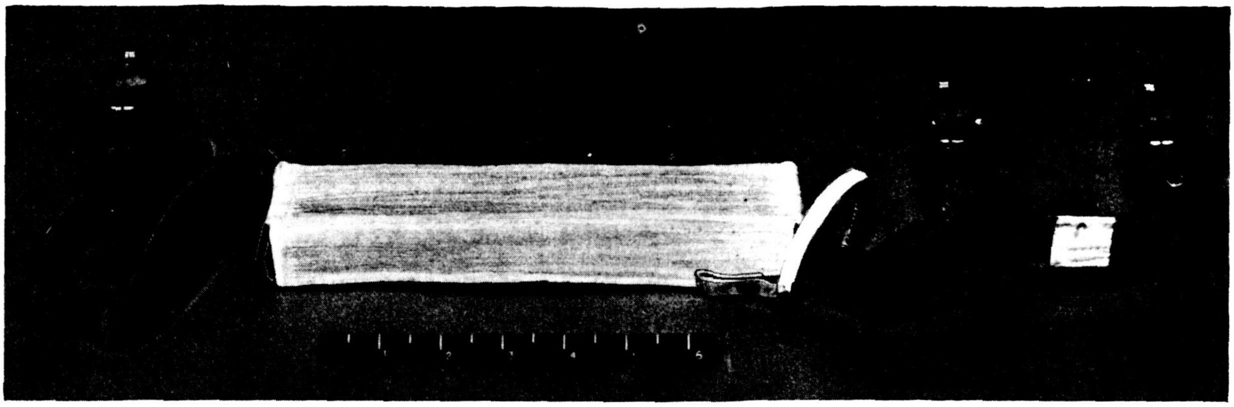


FIGURE 2-9: Apollo 9 Extravehicular Lifeline

Transearth EVA operations were performed on the Apollo 15 and 16 missions. The primary purpose of the EVA mission was to retrieve a 24 inch (19.3 inches in diameter by 6.2 inches wide and weighing 85 pounds) panoramic camera cassette and a 3 inch (10.5 inches in diameter by 8.5 inches wide and weighing 27 pounds) mapping camera cassette from the Scientific Instrument Module (SIM) located on the Command Service Module (CSM). Other objectives were to evaluate EVA hardware and procedures, to inspect the SIM bay and to evaluate CSM EVA compatibility. Three excursions were made to the SIM bay (Figure 2-10) during the transearth EVA operations (ref. 2.4). Rectangular handrails and handholds were used to translate to and from the worksite. Foot restraints (adjustable Gemini dutch shoes) and rigid handholds were used to retrieve the cassettes from the SIM receptacles. Each of the camera cassettes was attached

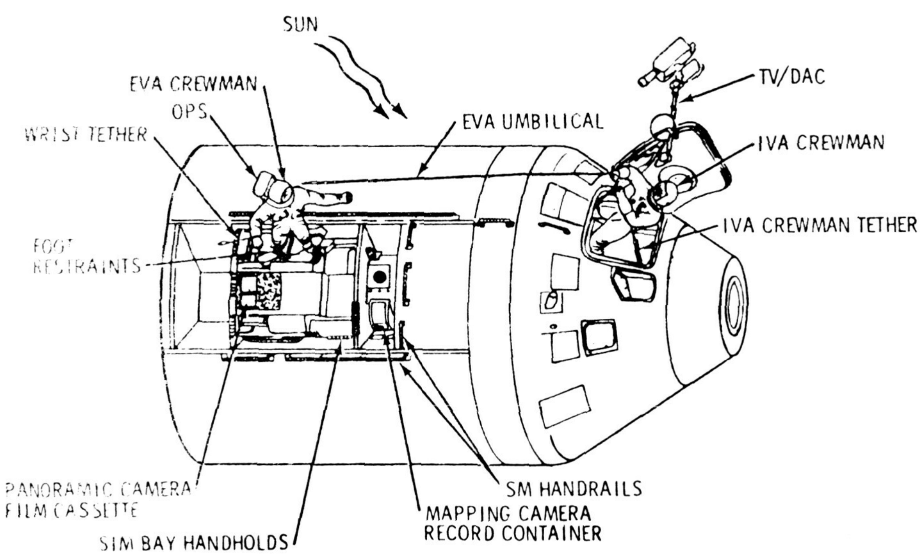


FIGURE 2-10: Apollo 15 EVA Film Magazine Retrieval

to the EVA crewman by a wrist tether during translation. The film cassettes were retrieved during the first two trips, and the other trips were used to examine the SIM bay for any abnormalities and to report the general condition of the instruments and spacecraft. In addition to the camera film cassette retrieval activities, a microbial response experiment (M191) was conducted on Apollo 16. This experiment required the EVA crewman to expose a self-contained Microbial Environment Exposure Device (MEED) to space radiation for a specified period of time near the end of the transearth EVA period. The MEED was returned to earth for laboratory analysis of the exposed micro-organisms.

No problems were encountered during the Apollo transearth operations. All mobility aids and restraint systems were completely adequate for performing the EVA functions. Conclusions from the Apollo transearth EVAs indicate that extravehicular operations should be considered for use in all future missions where a specific need for it exists, where the EVA operations will enhance mission success, and where the activity will provide a significant contribution to science and manned spaceflight.

2.2 CURRENTLY PLANNED EVA APPLICATIONS

2.2.1 Apollo 17 EVA

In addition to the extensive lunar extravehicular exploration and experimentation planned for the Apollo 17 mission, transearth EVA functions similiar to those performed on Apollo 15 and 16 are currently scheduled. The panoramic and mapping camera film cassettes will be retrieved from the SIM bay during the EVA mission. Additional transearth EVA functions may be scheduled. The Apollo 17 EVA mission timeline allots approximately 70 minutes for the conduct of transearth EVA. The allotted time includes hatch opening and closing operations.

2.2.2 Skylab EVA

Beyond the near future Apollo 17 lunar flight, the Skylab cluster is the only presently approved orbital space program that will utilize manned EVA to support mission objectives. The Skylab cluster consists of a Saturn Workshop (SWS) with an Apollo Command Service Module (CSM) docked to it (Figure 2-11). The SWS is composed of an S-1VB Orbital Workshop (OWS), an Airlock Module (AM), a Multiple Docking Adapter (MDA), a Saturn V Instrument Unit (IU), and an Apollo Telescope Mount (ATM).

The Airlock Module and the Apollo Telescope Mount are the two primary components involved in the performance of manned extravehicular operations. The AM provides a pressurized passageway between the MDA and the OWS. It contains the airlock for EVA and the supply, distribution, and control center for cluster atmosphere and thermal control. It also contains the equipment for electrical-power control and distribution to OWS, MDA, and the AM, and it provides support for cluster communications and data handling, including delayed-time voice communications with the ground. The ATM constitutes a solar observatory with the ability to observe, monitor, and record the

structure and behavior of the sun, particularly solar-flare activity. It also includes attitude controls and experiment pointing for the entire cluster, and, of importance to extravehicular operations, it incorporates provisions for servicing the solar astronomy instrumentation used in collecting solar activity data.

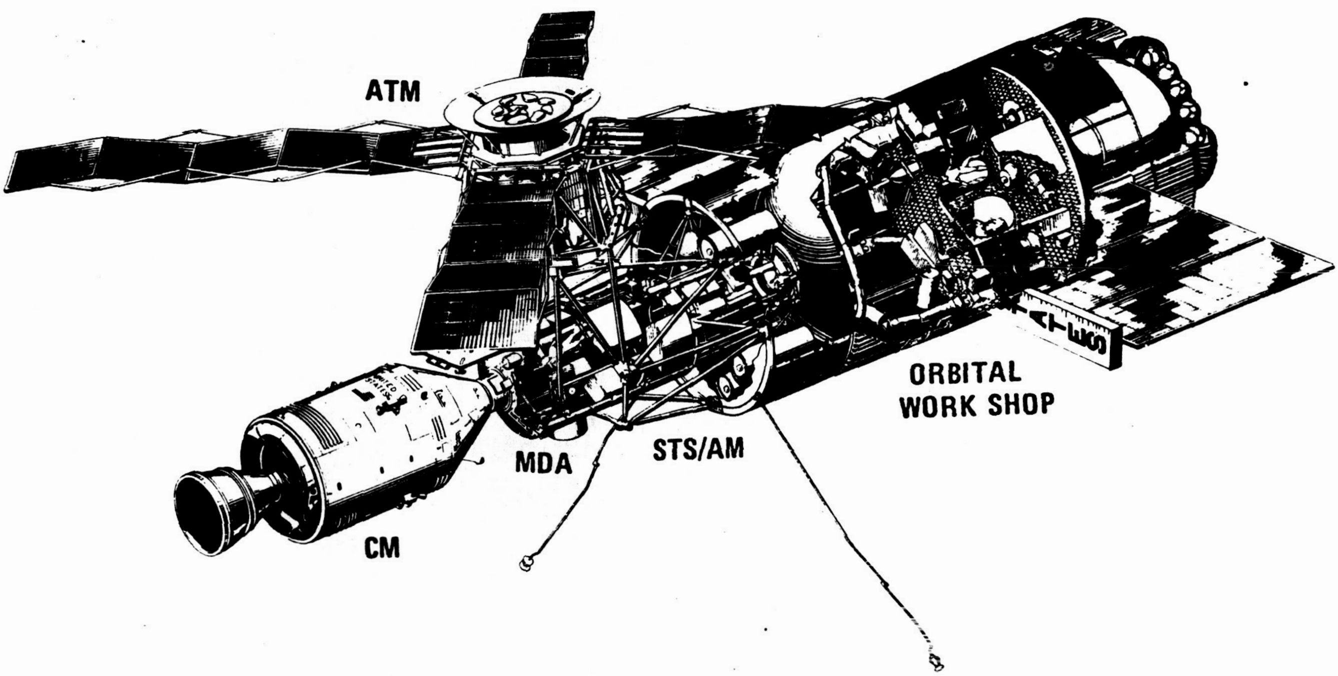


FIGURE 2-11: Skylab Cluster Configuration

One of the many objectives of the Skylab earth-orbital program is the collection of photographic data on solar activity -- data which is initially recorded by instrumentation in the ATM canister. This objective is partially fulfilled by employing manned EVA to service the ATM canister. The primary EVA activities during the 28-day and the two 56-day missions consist of retrieval of thermal coating samples. Each film magazine removal/replacement task involves one EVA crewman translating between the AM hatch and three workstations on the ATM, removing and/or replacing six film magazines, and returning the expended magazines to the AM. A second EVA crewman will be located outside the AM hatch to support the film retrieving astronaut, to manage his umbilical, and to assist in performing the tasks. A third crewman is partially suited and working in the MDA, monitoring subsystems and serving

as safety observer. Six separate EVA missions will be performed, each lasting approximately two and one-half hours (ref. 2.3). The major Skylab EVA functions currently being planned are listed in Table 2-3.

TABLE 2-3: EVA Associated Functions Planned on Skylab

SKYLAB/FUNCTION/TASK
• Crewman translation and body stabilization • Mobility aid evaluation • Cargo transfer - powered • Cargo transfer - mechanical assist (contingency) • Film magazine removal/replacement • Worksite evaluation (5 workstations) • Restraint systems evaluation (Skylab foot restraints) • Worksite activation • Camera deployment and operation (16mm and T.V. camera) • Umbilical management evaluation • Coating sample retrieval • Monitoring (EVA task performance techniques) • Ingress/egress (hatch and workstation) • Photography • Support equipment replacement (contingency - spare FTB replacement) • IVA experiments for developing EVA hardware - Experiment M 509 (evaluation of HHMU and ASMU - Automatically Stabilized Maneuvering Unit) - Experiment T 020 (evaluation of the FCMU - Foot Controlled Maneuvering Unit)

The EVA crewman's support equipment, operational techniques, and procedures developed and tested during the Gemini and early Apollo flights have been refined for Skylab to yield a reliable operating competency that can be used almost routinely to perform functions external to the spacecraft. The EVA support equipment consists of standard rectangular handrails and handholds for crewman translation and body positioning, foot restraints for worksite stabilization (Figure 2-12), and powered extendible booms as the primary cargo (film magazines) transfer system (Figure 2-13). The extendible booms, or, Film Transportation Booms (FTB), along with several pieces of support hardware, including film magazine clusters (i.e., trees, Figure 2-14), tree receptacles, stowage containers, stowage hooks, and equipment tethers, are used to aid in the film magazine handling operations. The majority of the EVA work functions are performed at the Airlock Module/Fixed Airlock Shroud (AM/FAS) workstation near the AM egress hatch (Figure 2-15), the ATM center workstation (Figure 2-16), the film transfer workstation, and the sun end film magazine retrieval workstation (Figure 2-17). A listing of the major EVA equipment components located at each of the Skylab EVA worksites is presented in Table 2-4.

During each of the six Skylab EVA missions, one of the EVA crewmen will be required to translate approximately 24 ft. from the AM hatch to the center workstation and about 30 ft. to the sun end workstation. Numerous manipulative tasks at each of the Skylab workstations are required during nominal EVA operations. These tasks include actuation or manipulation of the following:

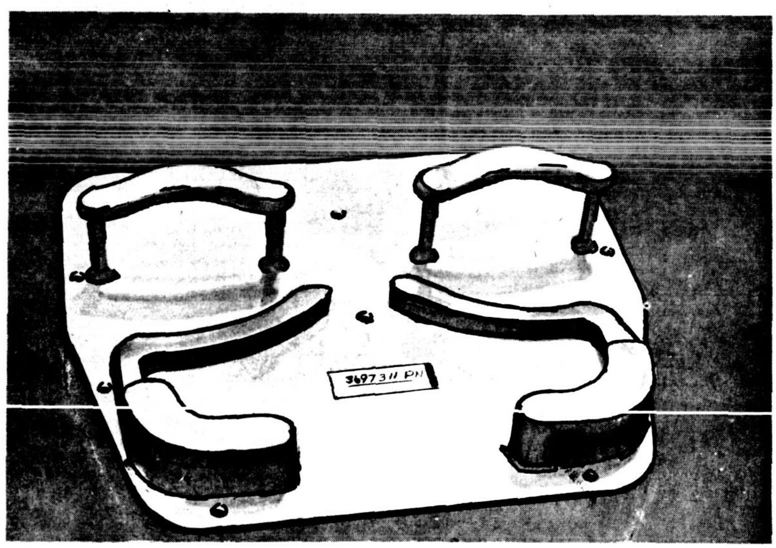


FIGURE 2-12: Skylab EVA Foot Restraints

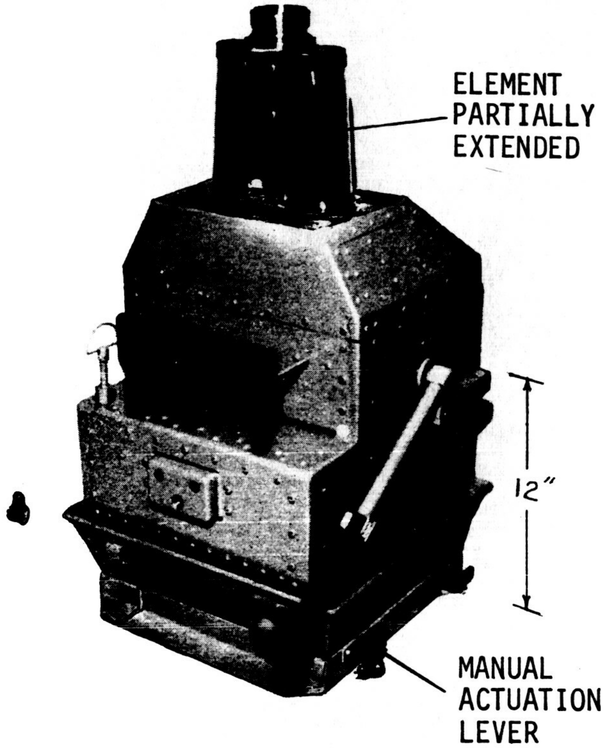
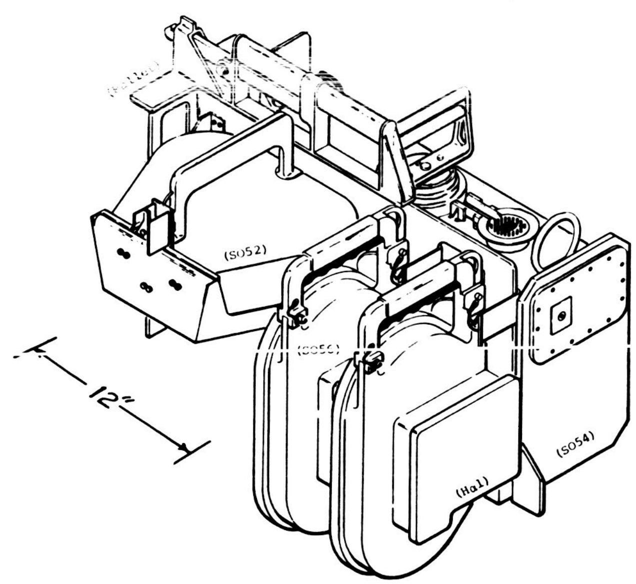


FIGURE 2-13: Skylab Prime Cargo Transfer System -- Film Transfer Boom (FTB)

FIGURE 2-14: Skylab Film Transportation Tree with Associated Film Magazines



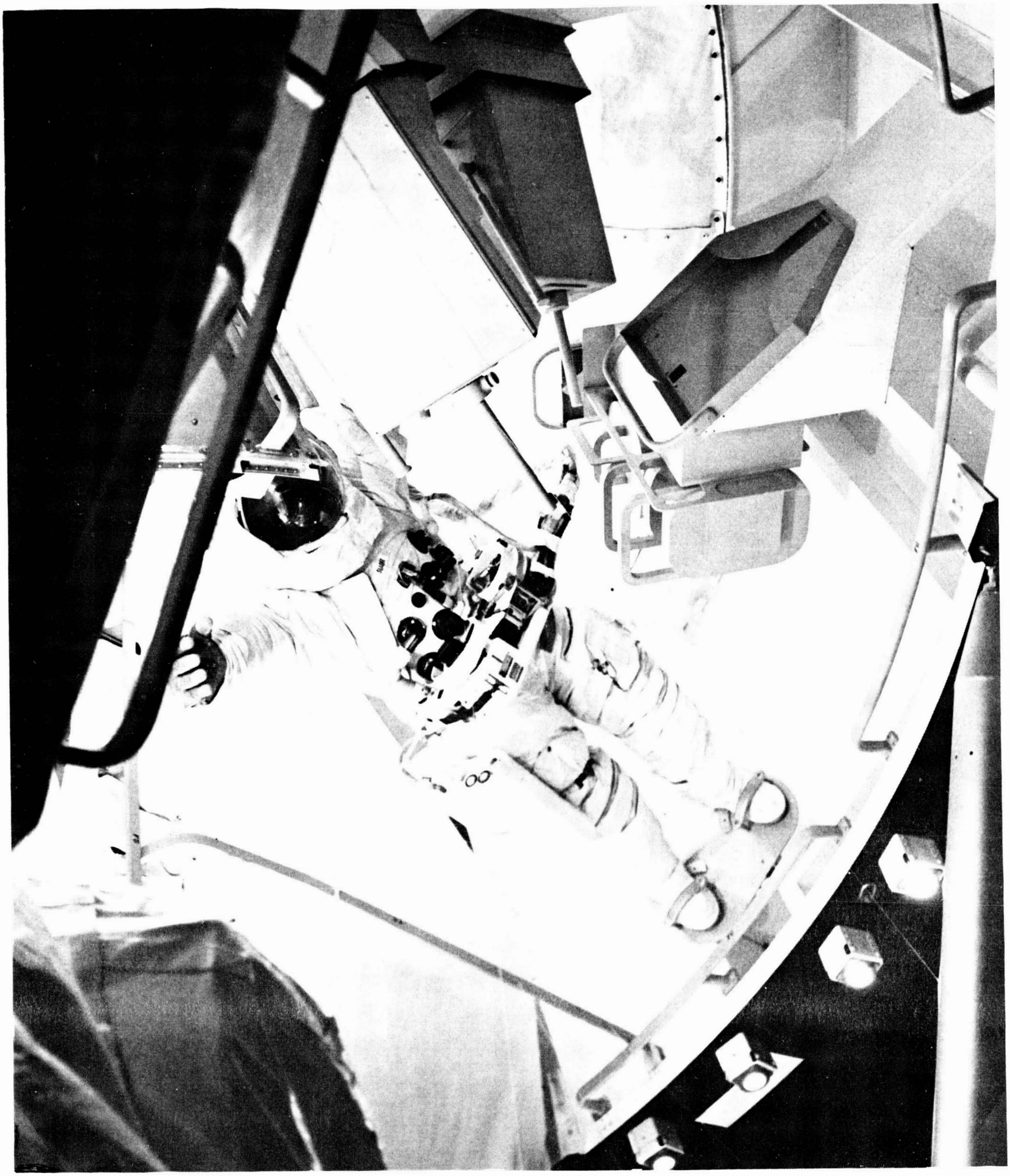


FIGURE 2-15: Skylab Airlock Module/Fixed Airlock Shroud Workstation Area

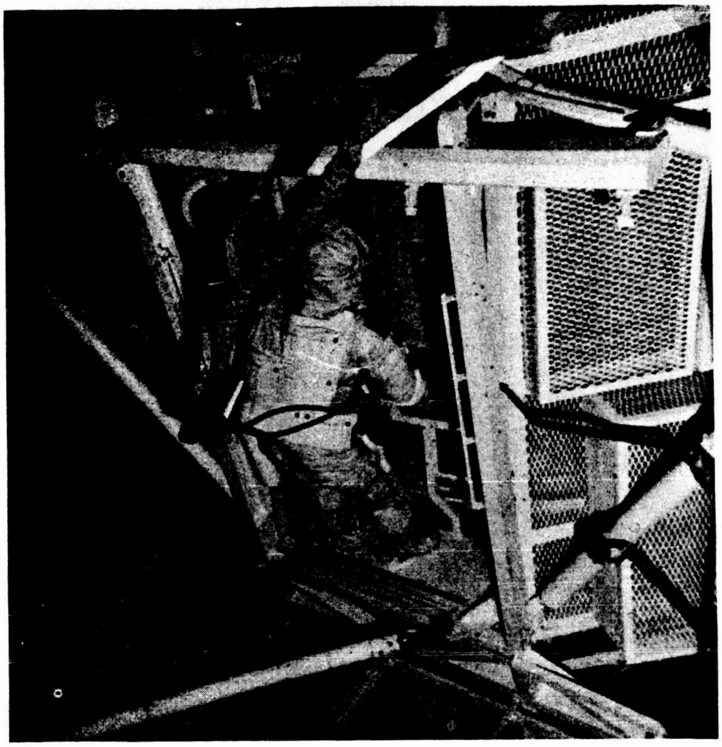


FIGURE 2-16: Skylab ATM Center Workstation Area - Water Immersion Mockup

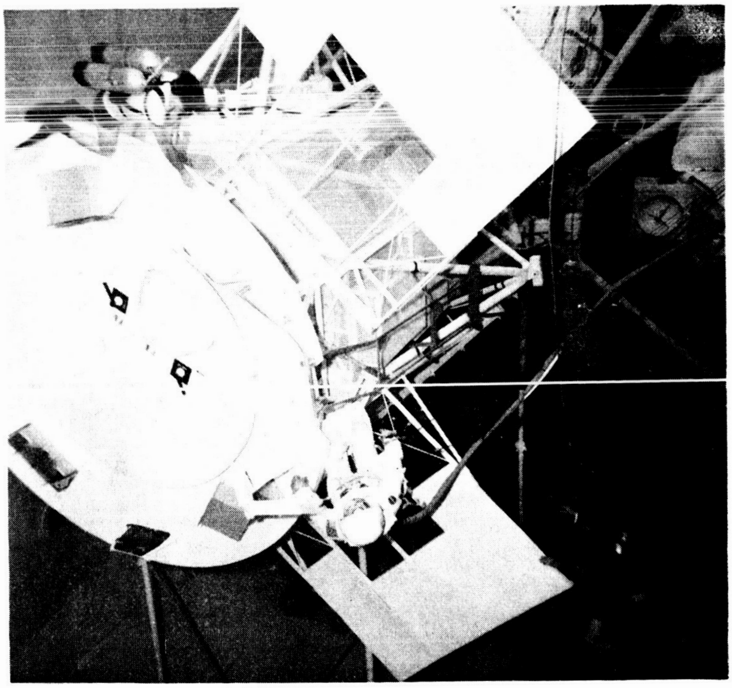


FIGURE 2-17: Skylab ATM Sun End Workstation Area - Water Immersion Mockup

TABLE 2-4: Skylab EVA Task Support Hardware

MAJOR EVA EQUIPMENT COMPONENTS AT SKYLAB WORKSITES		
AM/FAS WORKSITE	ATM CENTER WORKSTATION	TRANSFER AND SUN END WORKSTATION
• AM/FAS Workstation Foot Restraints	• Center Workstation Foot Restraints	• Transfer Workstation Foot Restraints
• Center Workstation Tree Receptacle	• Crewman Protective Screen	• Sun End Workstation Foot Restraints
• Sun End Tree Receptacle	• Center Workstation Area Lights	• Sun End Area EVA Lights
• Center Workstation FTB and Receptacle	• Clothesline Attach Bracket	• Clothesline Attach Bracket
• Sun End Workstation FTB and Receptacle	• ATM Canister Rotation Control Panel	• Film Magazine Access Doors and Handles
• Spare FTB and Receptacle	• Film Magazine Access Doors, Handles, and Launch Locks	• Film Magazine Temporary Stowage Container
• FTB Film Magazine Hooks	• Center Workstation Area Handrails and Handholds	• Sun End Workstation Area Handrails and Handholds
• Film Magazine Temporary Stowage Hooks	• Translation Path Handrails	• Translation Path Handrails
• FTB Control Panel	• Umbilical Clips	• Checklists
• FTB Manual Actuation Controls	• Film Magazine Temporary Stowage Hooks	
• Center Workstation Clothesline and Container	• Checklists	
• Sun End Workstation Clothesline and Container		
• FAS Area EVA Lights		
• Photographic Equipment		
• Umbilical Clips		
• FTB Replacement Workstation		
• FAS Area Handrails and Handholds		
• Checklists		

- FTB control panel
- FTB film magazine/tree hook
- Film magazine temporary stowage hook
- Film tree/receptacle interface
- Film magazine/tree interface
- ATM canister rotation control panel
- Center workstation film access door launch locks
- Center workstation access door latching operations
- Film magazine/receptacle interface
- Film magazine launch locks
- Film magazine stowage containers
- Umbilical clamps

During the six Skylab EVA missions, approximately 1500 pounds (earth weight) of cargo (film magazines) will be handled by the EVA crewmen. In the event of failure of a primary cargo transfer system (i.e., FTB) or other system malfunctions, additional contingency operations, such as electrical connector disconnect/connect, FTB replacement, failed FTB stowage, backup cargo transfer system deployment, manual sun end solar astronomy instrument aperture door actuation, and contingency cargo transfer system (endless clothesline, Figure 2-18) manual operations will be required.

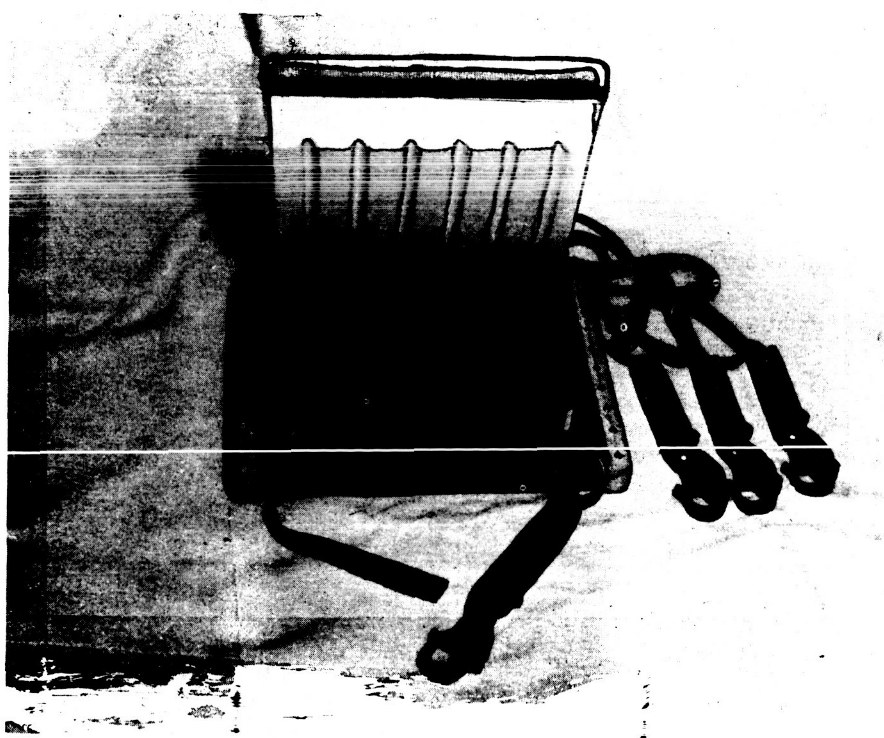


FIGURE 2-18: Skylab Contingency Cargo Transfer (Clothesline) System Partially Stored in Launch Container

The physical and performance characteristics of the Skylab EVA support hardware, including the space suits and life support systems, will be contained in Chapter III. Table 2-5 presents a summary of the support equipment used on each of the previous orbital EVA missions through Apollo 15 and the equipment currently scheduled for the remaining Apollo and Skylab Programs. The primary characteristics of the support equipment are included.

2.3 TYPICAL EVA TASK DESCRIPTIONS

An assessment of the orbital EVA operations conducted during the Gemini and Apollo Programs, of those EVA applications planned for the Skylab Program, and of projected space activities (Space Station, Shuttle, SOAR and RAM) has yielded numerous functions that can be performed by man outside the space vehicle (refs. 2.6 through 2.8). Several of the identified functions were combined into a single function, and the list was reduced to the following:

- Deploy/Retract
- Cargo Transfer
- Assembly/Mating
- Maintain
- Operate/Monitor
- Inspect/Diagnose
- Remove/Replace
- Repair/Refurbish
- Data Acquisition
- Satellite Deploy/Recover
- Crewman Translation
- Astronaut Rescue

The major EVA task functions required on each operational, design, and research mission can be classified under one of the twelve functions shown above. The specific requirements associated with each extravehicular function will depend upon the particular mission. To aid the planners and designers who are considering future manned EVA in classifying extravehicular functions and in correlating mission/experiment support requirements with manned EVA capabilities, a description of each typical function was determined. These task functions are contained in Table 2-6. The task function classifications and descriptions are used in identifying candidate manned EVA mission applications on potential future space programs in the following section.

2.4 CANDIDATE EVA MISSION APPLICATIONS

An analysis of proposed orbital space missions under study, including the modular Space Station, the Space Shuttle, the Research and Applications Module (RAM) and the Shuttle Orbital Applications and Requirements (SOAR) programs, has yielded numerous candidate requirements for operations to be performed outside the orbiting space vehicle. These candidate requirements were

TABLE 2-5: Summary of EVA Equipment

	PARAMETER	GEMINI MISSION IV	GEMINI MISSION IX-A	GEMINI MISSION X	GEMINI MISSION XI	GEMINI MISSION XII	APOLLO MISSION 9	APOLLO MISSION 11	APOLLO MISSION 12	APOLLO MISSION 14	APOLLO MISSION 15		APOLLO MISSION 16		APOLLO MISSION 17		SKYLAB MISSION *
GENERAL	STATUS	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete		Complete		Approved		Approved
	EVA DURATION (HR:MIN)																
	• Total	:36	2:07	1:29	2:43	5:30	:46	2:32	7:43	9:25	20:57		≈21:24. hr.		19-22 hr.		15 hr.
	• Orbital	:36	2:07	1:29	2:43	5:30	:46										
	- Standup			:50	2:10	3:24											
	- Umbilical	:36	2:07	:39	:33	2:06											15 hr.
	• Lunar							2:32	7:43	9:25	20:19		20:14 hr.		18-21 hr.		
	- Standup										:33						
	- Traverse							2:32	7:43	9:25	Three EVAs Totalling 19:46		Three EVAs of Totalling 20:14		Three EVAs of 6-7 hrs. ea.		
	• Deep Space										:38		≈ 1 hr.		1 hr.		
	NUMBER OF EVAs	1	1	2	2	2	1	1	2	2	5		4		4		6
LIFE SUPPORT/PRESSURE SUIT SYSTEMS	CREW PRESSURE SUITS	G4C	G4C	G4C	G4C	G4C	A-7L	A-7L	A-7L	A-7L	(a) A-7L-B	(b) A-7L-B	(a) A-7L-B	(b) A-7L-B	(a) A-7L-B	(b) A-7L-B	A-7L-B
	LIFE SUPPORT SYSTEMS (PRIMARY)	VCM(c)	ELSS(d)	ELSS	ELSS	ELSS	-6 PLSS(e)	-6 PLSS	-6 PLSS	-6 PLSS	-7 PLSS	Umb	-7 PLSS	Umb	-7 PLSS	Umb	ALSA(f)
	• Mounting	Chest	Chest	Chest	Chest	Chest	Back	Back	Back	Back	Back		Back		Back		Chest
	• Weight (lbs.)	7.75	42	42	42	42	84	84	84	84	103		103		103		30
	• Volume (in.^{3})	250	1350	1350	1350	1350	5100	5100	5100	5100	5100		5100		5100		
	• Cooling	Gas	Gas	Gas	Gas	Gas	LCG(g)	LCG	LCG	LCG	LCG	Gas	LCG	Gas	LCG	Gas	LCG
	• Oxygen Supply	25' Umb(h)	25' Umb	50' Umb	30' Umb	25' Umb	SC(i)	SC	SC	SC	SC	Umb	SC	Umb	SC	Umb	60' Um.
	• Operating Pressure (psi)	3.9	3.7	3.7	3.7	3.7	3-4	3-4	3-4	3-4	3-4	3-4	3-4	3-4	3-4	3-4	3-4
	• Flow Rate (lbs./hr.)	8.2	5.1-7.8	5.1-7.8	5.1-7.8	5.1-7.8	5.5	5.5	5.5	5.5	5.5	10-12	5.5	10-12	5.5	10-12	7.9-9
	• Metabolic Cooling (Btu/hr.)		1400-2000	1400-2000	1400-2000	1400-2000	3 hr./1600	See Apollo 9	See Apollo 9	See Apollo 9	Total 6400	1200-1800	Total 6400	1200-1800	Total 6400	1200-1800	2000 Avg. 2500 Peak
	LIFE SUPPORT SYSTEM (SECONDARY)	SC(i)	SC	SC	SC	SC	OPS(j)	OPS	OPS	OPS	OPS	OPS	OPS	OPS	OPS	OPS	SOP(k)
	• Duration (min.)	9	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
	• Weight (lbs.)	In VCM	In ELSS	In ELSS	In ELSS	In ELSS	42	42	42	42	42	42	42	42	42	42	
	• Volume (in.^{3})	In VCM	In ELSS	In ELSS	In ELSS	In ELSS	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	468

REMARKS
* Combination of All Skylab #1 Flights
a. Lunar EVA (Same on Following Sheets)
b. Deep Space (Same on Following Sheets)
c. Ventilation Control Module
d. Extravehicular Life Support System
e. Portable Life Support System
f. Astronaut Life Support Assembly
g. Liquid Cooling Garment
h. Umbilical
i. Self-Contained
j. Oxygen Purge System
k. Secondary Oxygen Pack

TABLE 2-5: Summary of EVA Equipment (Cont'd.)

PARAMETER	GEMINI MISSION					APOLLO MISSION										SKYLAB MISSION *
	IV	IX-A	X	XI	XII	9	11	12	14	15		16		17		
STABILIZATION SYSTEMS																
HANDHOLDS																
• Fixed				•	•											
• Flexible - Velcro Backed Portable		•														
• Rigid - Velcro Backed Portable					•											
• Pip-Pin					•											
• U-Bolt					•											
• Apollo Cross Section						•					•		•		•	•
TETHERS																
• Wrist						•					•		•		•	
• Waist					•						•		•		•	•
• Standup			•	•	•											
• Straps on Suit Legs				•	•											
• Support																
- U-Bolt Attach Device					•											
- Pip-Pin Attach Device					•											
FOOT RESTRAINTS																
• Dutch Shoes				•	•	•					•		•		•	
• Heel Clips																•
• Toe Bar		•														
OTHER																
• Pip-Pin Antirotation					•											
TRANSLATION / TRANSFER SYSTEMS																
POWERED[a]																
• AMU (D-012)		•														
• HHMU	•		•	•												
• AMU (M-509)																•
HANDRAILS																
• Telescoping					•											
• Rectangular		•	•	•	•											
• Large Cylindrical (1.38" Dia.)		•			•											
• Small Cylindrical (.317" Dia.)					•											
• Apollo Cross Section						•					•		•	•	•	•
• Dual Rails																•
TRANSLATION DISTANCE FROM HATCH (Ft. Approx.)																
• Assisted	25'		27'								30'		30'		30'	60'/EVA
• Unassisted		25'	12'	12'	25'											
CARGO TRANSFER																
• Total Cargo Weight (lbs. approx.)																250 lbs/EVA
• Manual (M)/Manual Actuation (MA)		M	M	M	M	M					M		M		M	MA:CL (b)
• Powered																•

REMARKS a. AMU - Astronaut Maneuvering Unit (Cancelled During Flight)
HHMU - Hand Held Maneuvering Unit
AMU - Astronaut Maneuvering Unit (IVA Evaluation)

b. Clothesline

* Combination of all Skylab #1 Flights

TABLE 2-5: Summary of EVA Equipment (Cont'd.)

	PARAMETER	GEMINI MISSION					APOLLO MISSION							SKYLAB MISSION *
		IV	IX-A	X	XI	XII	9	11	12	14	15	16*	17*	
VEHICLE SUPPORT SYSTEMS	WORKSITES													
	• Prepared	GH(a)	GH,AS(b)	GH	GH, AS	GH,AS, TDA(c)	LH,CH(d)				SIM(e) Bay	SIM Bay	SIM Bay	VF, VC, VS, VT(f)
	• Unprepared		•	•	•									
	WORKSITE TOOLS/AIDS													
	• Umbilical Guard	•												
	• Umbilical Pigtail					•								
	• Umbilical Clip					•								•
	• Cutters		•											
	• Wrench					•								
	• Electrical/Fluid Quick Disconnect					•								
	• Tether Clamp					•								
	• Tethers			•	•	•								
	• Tether Hooks		•			•					•	•	•	•
	• Pip-Pins					•								•
	• U-Bolts					•								
	EVA HATCHES (APPROX. CLEARANCE)													
	• Gemini/Skylab	22"x40"	22"x40"	22"x40"	22"x40"	22"x40"								22"x40"
	• Command Service Module						20"x24"	20"x24"	20"x24"	20"x24"	20"x24"	20"x24"	20"x24"	
	• Lunar Module						28"x30"	28"x30"	28"x30"	28"x30"	28"x30"	28"x30"	28"x30"	
	LIGHTING		•			•	•				•	•	•	•
	AIRLOCKS													80" Long x 65" Dia.
	EVA MONITORING													
	• Visual	•	•	•	•	•	•	•	•	•	• •	• •	• •	•
	• Video							•	•	•	• •	• •	• •	•
	• Audio	•	•	•	•	•	•	•	•	•	• •	• •	• •	•

REMARKS
a. Gemini Hatch
b. Adapter Section
c. Target Docking Adapter
d. LH: Lunar Module Hatch
CH: Command Service Module Hatch
* Combination of all Skylab #1 Flights
e. Service Module Experimentation Bay
f. VF: Airlock/FAS Workstation
VC: Center Workstation
VS: Sun End Workstation
VT: Transfer Workstation

TABLE 2-6: Classification of Typical EVA Tasks

TASK	TASK DEFINITION
DEPLOY/ RETRACT	*DEPLOYMENT* is the arrangement, extension, placement, unfolding, positioning, etc., of spacecraft components, systems, subsystems, or experiment apparatus and the securing of their equipment into its programmed location and configuration. *RETRACTION* is the reverse function and includes the releasing of the securing device(s) and the retraction, folding, stowing, etc. of the equipment (e.g., *DEPLOY/RETRACT* antennas, sensors, booms, solar arrays, experiment samples, etc.).
CARGO TRANSFER	*CARGO TRANSFER* is the transfer, movement, transportation, etc., of materials from one stable point in free space to another, including: on/off loading, tethering/restraining, inflight stabilization, mass relocation, untethering/unrestraining, special handling, etc., accomplished either manually or assisted by crewman maneuvering equipment (e.g., *CARGO TRANSFER* of film packages/retrieval, experiment modules, supplies and expendables).
ASSEMBLE/ MATING	*ASSEMBLE/MATING* is the joining, securing, fitting together of two or more units, components, subassemblies, etc., into a complete system by the performance of various operations that may include: sealing/bonding/welding, making of electrical/fluid/mechanical connections, and the positioning/stabilization prior to and during tne installation (e.g., antenna assembly/erection, spacecraft assembly, kicker stage mating, meteoroid collection equipment, etc.).
MAINTAIN	*MAINTENANCE* is the performance of scheduled, periodic operations required to sustain system efficiency and may include: servicing, cleaning, focusing, vessel resupply, aligning, calibration, tightening, checkout, etc. (e.g., *MAINTENANCE* of sensors, cleaning lenses and coatings, resupply of fluids, etc.).
OPERATE/ MONITOR	To *OPERATE* is to conduct a series of tasks in a specific sequence to permit continuing performance of systems for meeting mission objectives and may include: activation, sequential control deactivation, etc. *MONITOR* is to watch, observe, check, and review the status/progress of events and operations for the purpose of verification, regulation, or feedback control (e.g., experiment or spacecraft system activation and performance evaluation).
INSPECT/ DIAGNOSE	*INSPECTION* is the performance of a critical appraisal or an examination to obtain or verify information concerning specific condition of an item(s) and may include: structural integrity, operational parameters, state of alignment, need to repair/refurbish, need to remove/replace, etc. Technique may be visual, ultrasonic, x-ray, etc. *DIAGNOSIS* is the investigation or analysis of the cause or nature of a condition or phenomenon (e.g., *INSPECTION/DIAGNOSIS* as to possible cause(s) and location of pressure leak in spacecraft shell, radiator degradation, thruster malfunction, etc.).

TABLE 2-6: Classification of Typical EVA Tasks (Cont'd.)

TASK	TASK DEFINITION
REMOVE/ REPLACE	*REMOVAL/REPLACEMENT* is the performance of various operations to remove, detach, displace a module or subassembly from an assembly/system and to replace it with a substitute or superseding item. This function may include: releasing, removing, storing, acquiring, replacing, aligning, installing, securing, etc., where special, complex aids should not be required (e.g., *REMOVAL/REPLACEMENT* of thruster modules, experiment modules, film canisters, etc.).
REPAIR/ REFURBISH	*REPAIR/REFURBISH* is the performance of appropriate corrective action to renovate, recondition, etc., a damaged or malfunctioning item and to restore it to a usable, operable state. This may include: nonscheduled replacement at component level, cutting, sealing/bonding/welding, etc. This function will normally require the use of special aids (e.g., *REPAIR/REFURBISHMENT* of solar array panels, meteoroid damage, thermal coating replacement, etc.).
DATA ACQUISITION	*DATA ACQUISITION* is the procurement, attainment or collection of factual information and measurements by sensor/recording equipment. This function may include: the positioning of sensors in proximity of phenomena of interest, the stabilization of sensors, data recording, deactivation of sensor/recorder, etc. (e.g., data or electromagnetic field intensities and patterns, still and movie photography, plasma wake measurements, etc.).
SATELLITE DEPLOY/ RECOVERY	*SATELLITE DEPLOYMENT* is the performance, or assistance in the performance, of various sequential operations that result in the launching or emplacement of free flying satellite/subsatellite spacecraft into a desired orbit and may include: pre-release inspection and checkout, satellite release, post-release inspection, etc. (e.g., *DEPLOYMENT* of experiment subsatellites, orbital storage vessels, automated spacecraft, etc.). *SATELLITE RECOVERY* is the performance or assistance in the performance of various operations to accomplish the retrieval/acquisition of a free flying satellite/subsatellite spacecraft from orbit (may be unstable and uncooperative) and the stabilization of it in the desired position. This function may include: satellite rendezvous, pre-recovery inspection, stabilization/grappling, disabling of stabilization system/despinning, removing appendages/expelling expendables, positioning and securing satellite in receptacle, attachment of support umbilicals, etc. (e.g., *RECOVERY* of experiment subsatellite(s), automatic spacecraft, etc.).
ASTRONAUT RESCUE	*ASTRONAUT RESCUE* is the acquisition, extraction, and retrieval of a disabled EVA astronaut from a hazardous environment and positioning him in a safe location. This may include: rendezvous, stabilization, securing, translation and obstacle avoidance, etc. (e.g., recovering astronaut from disabled Astronaut Maneuvering Unit, other spacecraft, structural entanglement, etc.).
CREWMAN TRANSLATION (EVA)	*CREWMAN TRANSLATION* is the safe scheduled movement, transfer, or transportation of crewmen from point to point in free space or on the exterior of a single or docked vehicle(s). Translation support equipment may include handrails/handholds, tethers, HHMUs, AMUs, etc. (e.g., *CREWMAN TRANSFER* between undocked vehicles, on the exterior surface of single or integrated vehicles or in the immediate proximity of any spacecraft.).

classified using the methodology presented in Section 2.3, and they are listed in Table 2-7. The candidate EVA tasks are based primarily on the January 1971 Reference Earth Orbital Research and Applications Investigation document (NHB 7150.1) and on the various contractor phase studies being performed. Several Functional Program Elements (FPEs) specified EVA as a requirement for mission completion; some indicated the need for EVA to enhance mission success, and others required EVA only as a "save-the-experiment" possibility. Most candidate FPEs, at the time of the EVA Guidelines document preparation, were not defined or developed enough to specify logically the exact EVA requirements. The rationale used in specifying the requirement for EVA in Table 2-7 included experiment module time in orbit, component life expectancy, inspection and maintenance requirements, experiment configuration change, expendable resupply, etc.

2.5 EVA EQUIPMENT DESIGN/SELECTION CONSIDERATIONS

In designing EVA support systems and equipment and in selecting hardware for specific EVA application on future space programs, investigations must be made concerning the hardware in relation to the man, the mission, the spacecraft, and the total program. In addition to these hardware considerations, attention must be given to specific on-orbit EVA support systems and to the ground based programs, facilities and equipment required to support the development and verification of the on-orbit hardware. The major on-orbit support systems which are common to all future missions utilizing manned EVA are identified below:

- Environmental Control and Life Support Systems
- Crew Protective Systems (Space Suits)
- Airlocks and Support Equipment
- Crew and Cargo Transfer Systems
- EVA Worksites
- External Lighting
- Communications and Telemetry
- Data/Information Management
- EVA Tools

The considerations that must be acknowledged concerning these on-orbit EVA support systems and operations relative to their integration and impact on the applicable space program are listed in Table 2-8. The EVA support systems considerations are divided into the following general classifications:

- EVA Mission/Function
- Spacecraft Hardware/Systems Integration
- Crew Physiology/Performance
- Subsystem Hardware/Equipment
- Familiarization/Simulation/Training
- Special

TABLE 2-7: EVA Applications on Future Missions

FUNCTIONAL GROUP LEGEND:

● - NORMAL FUNCTION

◐ - CONTINGENCY FUNCTION

○ - POTENTIAL FUNCTION

NO.	TITLE	DEPLOY/RETRACT	CARGO TRANSFER	ASSEMBLE/MATING	MAINTAIN	OPERATE/MONITOR	INSPECT/DIAGNOSE	REMOVE/REPLACE	REPAIR/REFURBISH	DATA ACQUISITION	SATELLITE DEPL/RECOV	CREWMAN TRANSFER	ASTRONAUT RESCUE	EVA
	EARTH ORBITAL FPE EXPERIMENTS													
	ASTRONOMY EXPERIMENTS													
A1	A-1 X-RAY STELLAR ASTRONOMY				○		◐	○						
A2	A-2 ADVANCED STELLAR ASTRONOMY				○		●	○						
A3	A-3A Photohel. XUV Spect. X-Ray Tele.				○		◐	○						
A4	A-3B Solar Coronagraph				○		●	○						
A5	A-3C Photoheliograph				○		◐	○						
A6	A-4A 0.9M Narrow Field UV Tele.				○		●	○						
A7	A-4B 0.3M Wide Field UV Tele.				○		●	○						
A8	A-5A Lower Energy Experiment				○		◐							
A9	A-5B High Energy Experiment				○		●							
A10	A-6 IR TELESCOPE				○		◐							
	PHYSICS EXPERIMENTS													
P1	P-1-1 Atmos. & Magnetospheric Science							○				●		▲
P2	P-1-2 Cometary Physics	○												
P3	P-1-3 Meteoroid Science	●					●	●						▲
P4	P-1-4 Small Astronomy Telescope				○			○						
P5	P-2-1 Invest. of Plasma Wake	○	○		○					○	●			
P6	P-2-2 Invest. of Plasma Res. & Harm.									○	●			
P7	P-2-3 Invest. of Wave-Particle	○						●		○	●			
P8	P-2-4 Invest. of Elect. & Ion Beam Prop									○	●			
P9	P-3 COSMIC RAY PHYSICS LABORATORY		○		○			○						
P10	P-4-4 Chemical Lasers							○						
P11	P-4-6 Gas Reactions in Space	○								○	●			
	EARTH OBSERVATIONS EXPERIMENT													
ES1	ES-1 EARTH OBSERVATIONS FACILITY		○		○			○						
	COMMUNICATIONS/NAVIGATIONS EXPERIMENTS													
C/N1	C/N-1-1 Optical Freq. Demon.				◐					○	●	●		▲
C/N2	C/N-1-2 MM Wave Com. & Prop. Sys.	●						●		○	●	●		▲
C/N3	C/N-1-3 Surv. Search & Rescue Sys.	○								○	●			
C/N4	C/N-1-4 Sat. Nav. Tech.									○	●			
C/N5	C/N-1-5 Onboard Laser Ranging				◐					○	●	●		▲
C/N6	C/N-1-6 Autonomous Nav. Sys.	●										●		▲
C/N7	C/N-1-7 Transmitter Breakdown Test						●							▲
C/N8	C/N-1-8 Terrestrial Noise Meas.			●				●						▲
C/N9	C/N-1-9 Noise Source Ident.			●				●						▲
C/N10	C/N-1-10 Suscept. of Terr. Sys.			●				●				●		▲
C/N11	C/N-1-11 Tropospheric Prop. Meas.			●				●				●		▲
C/N12	C/N-1-12 Plasma Prop. Exp.									○	●			
C/N13	C/N-1-13 Multipath Measurements									○	●			
	MATERIALS SCIENCE AND MANUFACTURING EXPERIMENTS													
-	No T/O Application													
	TECHNOLOGY EXPERIMENTS													
T1	Sky Background Brightness Meas.	●								●		●		▲
T2	Surface Degradation Meas.	●								●		●		▲
T3	Contaminant Cloud Composition Meas.	●								●		○		△
T4	Contaminant Dispersal Meas.	●								●		○		△
T5	IRTCM Optical Module Evaluation	●								●				▲
T6	Active Cleaning Technique (ACT)	●								●				▲
T7	Contamination Control Evaluation	●								●				▲
T8	T-2 FLUID MANAGEMENT						○							
T9	Astronaut Maneuvering Unit (AMU)									○		●	◐	▲
T10	Maneuvering Work Platform (MWP)									○		●	◐	▲
T11	Oxygen Recovery & Biowaste Resisto-jet	●								●		●		▲
T12	Thermal Coating Refurbishment	●								●		●		▲
T13	Leak Detection and Repair	●					●		●	●		●		▲
T14	Maint. Att. Cont. Prop. Sys.				●		●	●	◐	●		●		▲
T15	Adv. Guidance Subsys. Eval.	○									●	●		▲
T16	Space Exp. Effects on Matl.	●					○			●		●		▲
-	T-5 TELEOPERATIONS (Experiment to Qualify a FF T/O													
	LIFE SCIENCE EXPERIMENTS													
LS1	LS-6 LIFE SUPPORT & PROTECTIVE SYSTEMS						○			○				
LS2	LS-7 MANNED SYSTEM INTEGRATION						○			○	○			
	EARTH ORBITAL SPACE LABORATORIES/MODULES													
	CONFIGURATION ASSEMBLY													
S/M1	Delivery & Docking of Modules		○	○										
S/M2	Verif. of Mod/Mod Interface						◐		◐					
S/M3	Solar Array Support Struct. Deploy.	◐					◐		◐			○		△
S/M4	Solar Array Mast/Panel Deployment	◐					◐		◐			○		△
S/M5	Verification of Module Docking Aids						○							
S/M6	Verification of Att. Control Thrusters						○							
S/M7	Deploy/Verification of Antennas	◐					○							
S/M8	Deploy/Verification of Booms	◐					○							
	CONFIGURATION SERVICING													
S/M15	Module Delivery & Docking		○	○							○			
S/M16	Cargo/Propellant Resupply		○		○									
S/M17	Module Interface Seal Servicing						◐		◐					
S/M18	Solar Array Panels/Struct. Servicing						◐	◐	◐			○		△
S/M19	Docking Aids Servicing						○	○	○					
S/M20	Free Flying Module Retrieval													
S/M21	Antennas Servicing						◐	◐	◐			○		△
S/M22	Radiator Servicing						◐		◐					
S/M23	Attitude Control Systems Servicing						◐	◐	◐			○		△
S/M24	Module Exterior Shell Servicing						◐		◐			○		△

NO.	TITLE	DEPLOY/RETRACT	CARGO TRANSFER	ASSEMBLE/MATING	MAINTAIN	OPERATE/MONITOR	INSPECT/DIAGNOSE	REMOVE/REPLACE	REPAIR/REFURBISH	DATA ACQUISITION	SATELLITE DEPL/RECOV	CREWMAN TRANSFER	ASTRONAUT RESCUE	EVA
	EARTH ORBITAL AUTOMATIC SATELLITES													
	ORBITING ASTRONOMICAL OBSERVATORY (OAO)													
AS1	Deploy Satellite from Shuttle Storage					○	○				○	○		△
AS2	Retrieve Satellite from Orbit				○		○					○		△
AS3	Attach Satellite to Shuttle			○			○					○		△
AS6	Determine Spacecraft Fault						○					●		▲
AS7	Replace Battery Module							○				●		▲
AS8	Replace Power Module							○				●		▲
AS9	Replace Computer Module							○				●		▲
AS10	Replace Communication Module							○				●		▲
AS11	Replace Pri. Att. Stab. Mod.							○				●		▲
AS12	Replace Sec. Att. Stab. Mod.							○				●		▲
AS13	Replace Momentum Wheel Module							○				●		▲
AS14	Replace Attitude Control Module							○				●		▲
AS15	Replace Electronics Module							○				●		▲
AS16	Replace Electro-Mechanical Module							○				●		▲
	SYNCHRONOUS EQUATORIAL ORBITER (SEO)													
AS19	Deploy Satellite from Shuttle Stowage					○	○				○			
AS20	Retrieve Satellite from Orbit					○	○					○		
AS21	Attach Sat. to Shuttle Deploy./Ret.Sta.			○			○							
AS24	Determine Spacecraft Fault						○							▲
AS25	Replace Battery Module							○				●		▲
AS26	Replace Power Control Module							○				●		▲
AS27	Replace Solar Array Paddle Drive							○				●		▲
AS28	Replace Solar Paddle							○				●		▲
AS29	Replace Data Handling Module							○				●		▲
AS30	Replace Communications Module							○				●		▲
AS31	Replace Sensing & Flight Control Mod.							○				●		▲
AS32	Replace Momentum Wheel Module							○				●		▲
AS33	Replace Attitude Control Module							○				●		▲
AS34	Replace Photographic Module							○				●		▲
AS35	Replace Vidicon Camera Module							○				●		▲
	SMALL RESEARCH SATELLITE (SRS)													
AS40	Deploy SRSs from Shuttle Storage					○	○				○			
AS45	Assemble/Mating of Kicker Stage			●								○		△
AS46	Assemble/Mating of Subsatellite			●								○		△
AS47	Verification of Satellite Interface						●		◐			○		△
AS50	Verification of Payload						●		◐			○		△
AS51	Activation of Ant., Booms, & Solar Arr.					●								△
AS52	Activation of Payload							●		●				△
AS53	Retrieval of Payload Film, Sensors, etc.	●				○			◐			○		△
AS54	Servicing of Payload Expendables				●		◐					○		△
	EARTH ORBITAL SPACE TUG													
	CONFIGURATION SERVICING													
ST1	Module/Space Tug Interface Servicing						◐		◐					
ST2	Communication Antennas Servicing						◐	○	◐					
ST3	Thermal Radiators Servicing						◐		◐					
ST4	Exterior Shell Servicing						◐		◐					
ST5	Attitude Control System (RSC) Servicing						◐	◐	◐					
ST6	Docking Aid Servicing						○	○	○					
	AUTOMATIC SATELLITE SERVICING													
-	PAYLOAD SERVICING -See Automatic Satellite Sheets													
	EARTH ORBITAL SPACE SHUTTLE/PAYLOAD													
	PAYLOAD INTERFACE SERVICING													
S/P1	-Verif. of Docking Port/Mechanism						●		◐			○		△
S/P2	-Verif. of Payload/Strongback Mechanism	○					●		◐			○		△
S/P3	-Verif. of Envir. Protection Systems						●		◐			○		△
	AUTOMATIC SATELLITE SERVICING													
-	AUTOMATIC SATELLITE SERVICING -See Automatic Satellites													

EVA REQUIREMENTS LEGEND:

△ POTENTIAL EVA TASK

▲ NOMINAL EVA TASK

TABLE 2-8: EVA Systems Design/Selection Considerations

SYSTEM NOMENCLATURE: EC/LSS - UMBILICAL AND PORTABLE

EVA MISSION/FUNCTION

- EVA Mission Definition
- Frequency of EVA Operations
- Tool Requirements (Manual/Powered)
- Number of Crewmen Required at Worksite
- Number of Times Task is Performed

SPACECRAFT HARDWARE/SYSTEMS INTEGRATION

- Vehicle Description/Characteristics
- Location of EVA Worksite
- Spacecraft Manpower Support Requirements
- Translation Path to EVA Worksite
- Equipment Along Translation Route
- Umbilical/Tether Entanglement Characteristics
- Power Requirements from Spacecraft
- External Lighting Requirements
- Airlock Volume/Dimensions
- Airlock Hatch Size
- EC/LSS - Spacecraft Interface Requirements
- Spacecraft Interface Requirements
- Tool Interface Requirements
- Stowage Volume Required for Units
- Stowage Environment/Atmoshpere Required for Units
- Stowage Volume Required for Support
- Workstation Ingress/Egress Volume Available
- Working Volume Available at Worksite

CREW PHYSIOLOGY/PERFORMANCE

- Number of Crewmen Required for EVA Tasks
- EC/LSS Expendables Requirements
- System Donning/Doffing Time
- Number of Crewmen Required to Don/Doff
- Telemetry Requirements
- Environmental Monitoring Requirements
- Physiological Monitoring Requirements
- Performance Monitoring Requirements
- Man's Physiological Requirements/Limitations
- Man's Psychological Considerations
- Mobility Restrictions Due to EC/LSS Hardware
- Man's Task Performance Capabilities in EVA
- Time Required to Perform Task
- Prebreathing Requirements

SUBSYSTEM HARDWARE/EQUIPMENT

- EVA Qualified EC/LSS Hardware
- State of EC/LSS Equipment Development
- EC/LSS Equipment Operational Characteristics
- EC/LSS Equipment Performance Characteristics
- EC/LS System Status Monitoring Requirements
- Hardware Operational Lifetime
- Equipment Operational Time in EVA
- Hardware Shelf Life
- Recharge Capabilities (Portable)
- Recharge Time Required
- Space Suit - EC/LSS Interface Requirements
- Equipment Maintainability
- Equipment Reliability
- Equipment Transportability
- Preparation/Checkout Time
- EC/LSS Replacement Spares Requirements
- Spares Shelf Life
- Contamination Data/Limits
- Umbilical/Tether Characteristics
- System Volume/Size/Mass/Center of Gravity
- Total System Weight
- Replacement Spares Weight
- Special Equipment Design Requirements
- Special Equipment Qualification Requirements
- Cost of Existing Qualified Units
- New Hardware Development/Technology Costs
- Suit Cooling System (Suit H_2O Loop) Hardware
- Communications Requirements
- Space Suit External Configuration

FAMILIARIZATION/SIMULATION/TRAINING

- Equipment Testing/Qualification Requirements
- Simulation Requirements
- Simulation Equipment/Mockup Requirements
- Simulation Facilities Available
- Crewman Task Familiarization/Training
- Operational Procedures Development
- Maintenance Manual Development
- Equipment Maintenance/Repair Training

SPECIAL

- Crew Safety
- Backup/Emergency Systems Available

TABLE 2-8: EVA Systems Design/Selection Considerations (Cont'd.)

SYSTEM NOMENCLATURE: SPACE SUIT AND SUPPORT HARDWARE

EVA MISSION/FUNCTION

- EVA Mission Definition
- Frequency of EVA Operations
- Tool Requirements (Manual/Powered)
- Qualified EVA Controls and Displays
- Time Required to Perform Task
- Number of Times Task is Performed
- Restraint Requirements to Perform Task
- Required Degree of Manual Dexterity
- Crew Translation Distance
- Mobility Aid Requirements (Handrails/Handholds)
- Cargo Quantity to be Handled
- Total Number of Crewmen Required for EVA

SPACECRAFT HARDWARE/SYSTEMS INTEGRATION

- Vehicle Time on Orbit
- Translation Path to EVA Worksite
- Equipment Along Translation Route
- Power Requirements
- Umbilical/Tether Entanglement Characteristics
- Vehicle Manpower Support Requirements
- External Lighting Requirements
- Workstation Orientation/Location
- Workstation Ingress/Egress Volume Requirements
- Working Volume Required at Worksite
- Tool Interface Requirements
- Volume Required for Support Equipment Stowage
- Suit Stowage Volume
- Suit Donning/Doffing Station Requirements
- Medical Support Capabilities
- Suit Drying System Requirements
- Stowage Environment

SUBSYSTEM HARDWARE/EQUIPMENT

- Space Suit Development/Equipment Costs
- EVA Qualified Suit Hardware
- EVA Equipment Operational Characteristics
- Suit System Weight
- Suit Replacement Spares Requirements
- Suit Hardware Operational Life
- Special Equipment Design Requirements
- Special Equipment Qualification Requirements
- Suit Maintainability/Reliability
- Suit Transportability
- Suit Shelf Life
- Waste Management Requirements
- Biomedical Support Hardware
- Communications Requirements
- Total Suit Anthropometrics
- Umbilical/Tether Characteristics
- Crewman Life Support Expendables
- Life Support System Performance Characteristics
- Life Support System Expendables Requirements
- Life Support System (Volume/Size/Mass)
- State of EVA Support Equipment Development
- Existing EVA Qualified Cargo Transfer Systems (Manual/Powered)
- Existing EVA Qualified Crew Translation Systems (Manual/Powered)
- Qualified Crewman/Cargo Restraint Systems
- Umbilical/Tether Management
- Suit Operating Pressure
- Suit's Ventilation Capability
- Suit Drying Time

CREW PHYSIOLOGY/PERFORMANCE

- Vehicle Cabin Pressure
- Vehicle Atmosphere (One or Two Gas System)
- Number of Support Personnel Required for Don/Doff
- Illumination Levels
- Suit Preparation/Checkout Time
- Force Requirements to Perform Task
- Crew Sizing
- Food and Water Requirements
- Duration of EVA
- Man's Physiological Limitations
- Man's Psychological Considerations
- Man's Task Performance Capabilities in EVA
- Force Capabilities of Suited Crewman
- Mobility Capabilities of Suited Crewman
- Reach Capabilities of Suited Crewman
- Crewman Time Limits in EVA
- Crewman/Suit External Volume
- Cargo Handling Capabilities
- Cargo Mass Handling Limits
- Status Self Monitoring
- Comfort Requirements
- In-Suit Time Limits
- Don/Doff Time Requirements
- Prebreathing Time Requirements
- Anticipated Metabolic Rates
- Anticipated Total Energy Expenditure

FAMILIARIZATION/SIMULATION/TRAINING

- Total Simulation Requirements
- Simulation Equipment/Mockup Requirements
- Simulation Facilities Available
- Crewman Familiarization/Training
- Operational Procedures Development
- Launch Operations Integration

SPECIAL

- Crewman Safety
- Crewman Rescue
- Backup/Emergency Systems
- Radiation Protection

TABLE 2-8: EVA Systems Design/Selection Considerations (Cont'd.)

SYSTEM NOMENCLATURE: AIRLOCKS AND EQUIPMENT

EVA MISSION/FUNCTION	SUBSYSTEM HARDWARE/EQUIPMENT
• EVA Mission Definition • Frequency of EVA • Mobility Aid Requirements • Number of Hatches • EVA Cargo Mass/Size/Volume	• Power Requirements (Lights, etc.) • System Expendable Requirement • Airlock Development Costs (to Orbit) • Airlock Equipment Costs • EVA Qualified Airlock Hardware • Airlock Operational Characteristics • Airlock Preparation/Checkout Time • Airlock System Weight • Airlock Replacement Parts Requirement • Airlock Hardware Operational Life • Replacement Parts Shelf Life • Total Pressure Suit Anthropometrics • Life Support System (Volume/Size Limits) • State of Airlock Support Equipment Development • Communications Requirements • Required Hatch Size • Qualified Crewman Restraint Systems • Qualified Cargo Restraint System
SPACECRAFT HARDWARE/SYSTEMS INTEGRATION	
• Vehicle Description/Characteristics/Orientation in Orbit • Vehicle Time on Orbit • Translation Path to Worksite • Vehicle/System Interface Requirements • Vehicle Integration • Vehicle Manpower Support Requirements • Lighting Requirements • Airlock Orientation/Location • Airlock Egress/Ingress Volume Requirements • Working Volume Required in Airlock • Umbilical Stowage Requirements • Life Support System Interface Requirements • Crewman/Suit External Volume	
CREW PHYSIOLOGY/PERFORMANCE	**FAMILIARIZATION/SIMULATION/TRAINING**
• Man's Physiological Limitations • Man's Psychological Considerations • Man's "Weightless" Task Performance Capabilities • Force Capabilities of Suited Crewman • Mobility Capabilities of Suited Crewman • Reach Capabilities of Suited Crewman • Visibility Capabilities of Suited Crewman • Decompression/Recompression Time • Decompression/Recompression Rate	• Total Simulation Requirements • Simulation Equipment/Mockup Requirements • Simulation Facilities Available • Crewman Familiarization/Training • Operational Procedures Development
	SPECIAL
	• Crewman Safety • Crewman Rescue • Backup/Emergency System

TABLE 2-8: EVA Systems Design/Selection Considerations (Cont'd.)

SYSTEM NOMENCLATURE: CREW AND CARGO TRANSFER

EVA MISSION/FUNCTION

- EVA Mission Definition
- Frequency of EVA Operations
- Tool Support Requirements
- Support Hardware Requirements
- Hardware Design Requirements
- Hardware Qualification Requirements
- Qualified EVA Controls and Displays
- Space Suit/Translation System Interface
- Cargo/Space Suit Interface
- Transfer/Translation Distance
- Cargo Quantity to be Handled
- Number of Times Task is Performed

SPACECRAFT HARDWARE/SYSTEMS INTEGRATION

- Vehicle Description/Characteristics/Orientation in Orbit
- Vehicle Time on Orbit
- Vehicle/System Interface Requirements
- System Power Requirements
- System Expendable Requirements
- External Lighting Requirements
- Worksite Orientation/Location
- Working Volume Required at Workstation
- Tool Interface Requirements
- Support Hardware Interface Requirements
- Total System Weight
- Volume Required for Support Hardware Stowage
- Cargo Packaging Requirements
- Airlock and Hatch Size/Shape
- Vehicle/System Integration
- Umbilical Management
- Crewman/Suit External Volume
- Vehicle Manpower Support Requirements

SUBSYSTEM HARDWARE/EQUIPMENT

- Support Hardware Power Requirements
- System Development Costs (to Orbit)
- System Equipment Costs
- EVA Qualified Transfer/Translation Hardware
- EVA System Operational Characteristics
- Hardware Spares Requirements
- Systems Operational Life
- Spare Shelf Life
- Hardware Maintainability
- Hardware Reliability
- System Flexibility
- Cargo/Transfer System Interface
- System Maintenance Requirements
- Systems Checkout Time
- Transfer System Stop Distance/Automatic Shutdown
- System(s) Manual Override
- Existing EVA Qualified Transfer/Translation System
- Qualified Cargo Restraint Systems
- Qualified Crewman Restraint Systems
- Communication Requirements
- Total Pressure Suit Anthropometrics
- Umbilical/Tether Characteristics
- Transfer System Cargo Limits
- Life Support System Performance Characteristics
- Life Support System (Volume/Size/Mass)
- State of EVA Support Equipment Development
- AMU

CREW PHYSIOLOGY/PERFORMANCE

- Number of Crewmen Required for System Operation
- Illumination Levels
- Total Energy Expenditure
- Estimated Metabolic Workloads Anticipated
- Transfer/Translation Rate
- Transfer/Translation System Loading/Unloading Time
- Transfer/Translation Attitude Control
- Man's Physiological Limitations
- Man's Psychological Considerations
- Man's Task Performance Capabilities in EVA
- Force Capabilities of Suited Crewman
- Mobility Capabilities of Suited Crewman
- Reach Capabilities of Suited Crewman
- Visibility Capabilities of Suited Crewman
- Time Required to Translate/Perform Transfer
- Restraint Requirements to Perform Transfer
- Cargo Mass Handling Limits
- Crewman Life Support Expendables
- Life Support System Expendable Requirements
- Crewman Time Limits in EVA

FAMILIARIZATION/SIMULATION/TRAINING

- Total Simulation Requirements
- Simulation Equipment/Mockup Requirements
- Simulation Facilities Available
- Crewman Familiarization/Training
- Operational Procedures Development

SPECIAL

- Crewman Safety
- Crewman Rescue
- Backup/Emergency Systems

TABLE 2-8: EVA Systems Design/Selection Considerations (Cont'd.)

SYSTEM NOMENCLATURE: EVA WORKSITES

EVA MISSION/FUNCTION

- EVA Mission Definition
- Classification of Task
- Frequency of EVA Operations
- Number of Crewmen Required at Worksite
- Working Volume Required at Worksite
- Worksite Preparation/Checkout Time
- Tool Requirements (Manual and Powered)
- Force Required to Perform Task
- Pressure Suit Anthropometrics
- Restraint Requirements to Perform Task
- Mobility Aids Required to Perform Task
- Umbilical/Tether Management

SPACECRAFT HARDWARE/SYSTEMS INTEGRATION

- Vehicle Description/Characteristics
- Vehicle Orientation in Orbit
- Vehicle Time on Orbit
- Worksite Hardware/Vehicle Interface Requirements
- Translation Path to EVA Worksite
- Equipment Along Translation Path
- Power Requirements (Lights, Equipment)
- Number of Worksites Required
- Spacecraft EVA Manpower Support Requirements
- Worksite Orientation/Location
- Prepared Worksite Requirements
- Workstation Ingress/Egress Volume Requirements
- Crewman Life Support Expendables
- Volume Required for Support Equipment and Spares Stowage
- Weight of Replacement Spares
- Life Support System Physical Characteristics
- Space Suit and Hardware Physical Characteristics

SUBSYSTEM HARDWARE/EQUIPMENT

- EVA Qualified Worksite Hardware
- EVA Equipment Operational Characteristics
- Worksite System and Subsystem Weight Penalty
- External Lighting Requirements
- Replacement Spares Requirements
- Spares Shelf Life
- Equipment Operational Life
- Type of Life Support System Required
- Umbilical/Tether Characteristics
- Life Support System Performance Characteristics
- Life Support System Physical Characteristics
- Life Support System Expendable Requirements
- Qualified EVA Controls and Displays
- Approved Mobility Aids (Handrails, Handholds)
- Equipment Reliability
- Equipment Maintainability
- Status of EVA Support Equipment Development
- Type of Restraints Required
- Type of Crew and Cargo Transfer System(s) Required
- EVA Qualified Restraint Systems
- EVA Qualified Crew/Cargo Transfer Systems
- Special Equipment Handling Requirements
- Systems and Equipment Flight Qualification
- Communication Systems
- Existing Qualified Equipment Cost
- New Hardware Development/Technology Cost

CREW PHYSIOLOGY/PERFORMANCE

- Man's Physiological Requirements/Limitations
- Man's Psychological Considerations
- Man's Task Performance Capabilities in EVA
- Force Emission Capabilities of Suited Crewman
- Reach Capabilities of Suited Crewman
- Visibility of Suited Crewman
- Illumination Levels Required
- Time Required to Perform Task
- Number of Times Task is Performed
- Approved Mass Handling Limits
- Life Support System Performance Characteristics
- Crewman Time Limits in EVA
- Translation Distance to Worksite
- Cargo Quantity to be Handled

FAMILIARIZATION/SIMULATION/TRAINING

- Design/Development Reviews Required
- Total and Part Task Simulation
- Simulation Techniques/Modes
- Simulation Equipment/Mockup Requirements
- Simulation Facilities Available
- Simulation Facilities Capabilities
- Simulation/Training Costs
- Crewman/Monitor Familiarization and Training
- Operational Procedures Development

SPECIAL

- Crewman Safety Requirements
- Crewman Rescue Capability
- Backup/Emergency Systems

TABLE 2-8: EVA Systems Design/Selection Considerations (Cont'd.)

SYSTEM NOMENCLATURE: EXTERNAL LIGHTING

EVA MISSION/FUNCTION	SUBSYSTEM HARDWARE/EQUIPMENT
• EVA Mission Definition • Sun Angle • Shadow Patterns • Tool Support Requirements (Manual/Powered) • Focus Configuration (Wide vs. Deep Field of Illumination) • Type of Task to Perform • Darkside/Lightside EVA • Frequency of Use • Duration of Each Use • Crew Translation Distance	• Lighting Development Costs • Lighting Equipment Costs • EVA Qualified Lighting Hardware • EVA Lighting Equipment Operational Characteristics • Lighting System Total Weight • Crewman/Light Protection • Lighting Replacement Spares Requirements • Lighting Equipment Operational Life • Spares Shelf Life • Special Support Equipment Design Requirements • Special Equipment Qualification Requirements • Lighting Equipment Maintainability • Lighting Equipment Reliability • New Hardware/Technology Costs • Lighting Equipment Portability • Type of Switch Control • Recharge Time for Applicable Equipment • Focus Adjustment • Unit Envelope Configuration • Cycles of Use (Number of Times Lights Can Cycle) • Number of Lights Required • Spectral Characteristics of Helmet/Visor • Suit/Life Support System Volume
SPACECRAFT HARDWARE/SYSTEMS INTEGRATION	
• Vehicle Description/Characteristics/Orientation in Orbit • Translation Path to EVA Worksite • Equipment Along Translation Route • Vehicle/Light Interface Requirements • Power Requirements • Worksite Orientation/Location • Workstation Ingress/Egress Lighting Requirements • Tool Interface Requirements • Obstruction • Pre-Launch Checkout • Volume Required for Support Equipment Stowage • Stowage Environment for Spares • Mobility Aids Requirements Location • Crewman Restraint Systems Location • Cargo Restraint Systems Location • Cargo Volume Requirements at the Worksites • Vehicle Time on Orbit	
CREW PHYSIOLOGY/PERFORMANCE	**FAMILIARIZATION/SIMULATION/TRAINING**
• Lighting Requirements for Controls and Displays • Illumination Levels • Man's Physiological Limitations • Man's Psychological Considerations • Visibility Capabilities of Suited Astronaut • Suited Crewman Reach Envelopes	• Total Simulation Requirements • Simulation Equipment/Mockup Requirements • Simulation Facilities Available • Crewman Familiarization/Training • Operational Procedures Development
	SPECIAL
	• Crewman Safety • Crewman Rescue • Backup/Emergency Systems

TABLE 2-8: EVA Systems Design/Selection Considerations (Cont'd.)

SYSTEM NOMENCLATURE: COMMUNICATION AND TELEMETRY

EVA MISSION/FUNCTION	SUBSYSTEM HARDWARE/EQUIPMENT
• EVA Mission Definition • Number of Channels Required • Distance Traveled from Prime Spacecraft • System Preparation/Checkout Time • Support Tool Requirements • Ground Support Equipment Requirements	• EVA Equipment Performance Monitoring Requirements • State of Data Management Systems Development • System Development Costs • System Equipment Costs • Cost of Existing Qualified Units • Existing EVA Qualified Equipment • Equipment Operational Characteristics • Equipment Performance Characteristics • System Weight • Replacement Spares Requirement • Equipment Operational Life • Equipment Shelf Life • Spares Shelf Life • Special Equipment Design Requirements • New Equipment Qualification Requirements • Equipment Transportability • System Volume/Size/Mass • Fault Isolation Ease • System Maintainability • System Reliability • New Hardware Development/Technology Costs • Backup System Requirements
SPACECRAFT HARDWARE/SYSTEMS INTEGRATION	
• Vehicle Description/Characteristics/Orientation in Orbit • Vehicle Time on Orbit • Vehicle/Ground/Space Suit Interface Requirements • Power Requirements • Spacecraft/Ground Manpower Support Requirements • System Compatibility • Tool Interface Requirements • Stowage Volume Required for Spare Equipment • Equipment Storage/Storage Environment • Labeling Support Requirements	
CREW PHYSIOLOGY/PERFORMANCE	**FAMILIARIZATION/SIMULATION/TRAINING**
• Crewman Biomedical Monitoring Requirements • Crewman Physiological Monitoring Requirements • Crewman Performance Monitoring Requirements • Crewman Behavioral Monitoring Requirements • Total Number of Crewmen Required for EVA	• Equipment Testing/Qualification Requirements • Crewman Equipment Operation Familiarization/Training • Operational Procedures Development • Maintenance Manual Development • Equipment Maintenance and Repair Training • Total Simulation Training Requirements
	SPECIAL
	• Crew Safety Requirements • Backup Emergency Requirements • Qualified Backup Emergency Systems • Caution and Warning Requirements

TABLE 2-8: EVA Systems Design/Selection Considerations (Cont'd.)

SYSTEM NOMENCLATURE: DATA/INFORMATION MANAGEMENT SYSTEMS

EVA MISSION/FUNCTION

- EVA Mission Definition
- Frequency of EVA Operations
- Duration of EVA
- Distance Traveled From Prime Spacecraft
- Destination of Data (Spacecraft, Earth)
- Quantity of Data Per Unit Time
- Number of Channels Required
- Tool Requirements
- Special Equipment Design Requirements

SPACECRAFT HARDWARE/SYSTEMS INTEGRATION

- Vehicle Description/Characteristics
- Spacecraft Manpower Support Requirements (Monitor, Control)
- Power Requirements
- Storage Volume Required for Spare Equipment
- Storage Environment/Atmosphere for Spares

CREW PHYSIOLOGY/PERFORMANCE

- Crewman Workload Allocation
- Crewman Physiological Monitoring Requirements
- Crewman Performance Monitoring Requirements
- Crewman Behavioral Monitoring Requirements
- Man's Performance Capabilities in EVA
- Total Number of Crewmen Required for EVA

SUBSYSTEM HARDWARE/EQUIPMENT

- EVA Equipment Performance Monitoring Requirements
- Spacecraft Manpower Support Requirements (Monitor, Control)
- Existing Qualified Systems in Use or Available
- State of Data Management Systems Development

- Sensors	- Displays
- Signal Conditioners	- Antennas
- Transmitters	- Audio
- Receivers	- Visual
- Recorders	- TV

- Type of System (Hardline, Telemetry, etc.)
- Type of Data (Film, Magnetic Tapes, Display, etc.)
- Equipment Operational Characteristics
- Equipment Performance Characteristics
- Hardware Operational Lifetime
- Equipment Shelf Life
- Equipment Transportability
- Replacement Spares Requirements
- Spare Shelf Life
- System Volume/Size/Mass
- System Weight
- Replacement Spares Weight
- New Hardware Development/Technology Costs
- New Equipment Qualification Requirements
- Cost of Existing Qualified Units
- System(s) Reliability
- System(s) Maintainability
- Ground Support Equipment Requirements
- Ground Support Personnel

FAMILIARIZATION/SIMULATION/TRAINING

- Equipment Testing/Qualification Requirements
- Crewman Equipment Operation Familiarization/Training
- Maintenance Manual Development
- Equipment Maintenance/Repair Training

SPECIAL

- Backup System(s) Requirements
- Crewman Safety Requirements
- Backup/Emergency Requirements
- Qualified Backup/Emergency Systems

Each of these items must be weighed in early tradeoff studies against other candidate systems capable of performing EVA. The list is intended to give the mission planners and designers an initial indication of the most "costly" parameters that should be considered. No attempt is made to develop a methodology for determining the optimum selection of manned EVA support systems, or to develop a selection criteria for specifying manual or mechanical means to perform extravehicular functions.

Numerous ground based facilities, equipment, and operations are required to support the development and verification of on-orbit EVA systems, hardware and procedures. The major ground based supporting operations that must be considered in planning orbital EVA missions are given below:

- EVA System and Equipment Testing/Flight Verification
- Simulation/Training Hardware
- Simulation/Training Facilities
- Operational Procedures Development/Verification

Table 2-9 contains a listing of the considerations that must be acknowledged by the mission planners and designers concerning these areas of the total EVA development program.

TABLE 2-9: EVA Systems/Hardware Development Considerations

MISSION SUPPORT REQUIREMENTS

EVA SYSTEM AND EQUIPMENT TESTING/FLIGHT VERIFICATION

- EVA Mission Definition
- Crewman/Equipment Interface Requirements
- Equipment Operational Characteristics
- Frequency of EVA Operations
- Duration of EVA
- Vehicle Time On-Orbit
- Crewman Safety Requirements
- Flight Hardware Operational Characteristics
- Spacecraft/EVA Equipment Interface Operations
- Testing Requirements
- Testing Facilities
- Types of Test
- Hardware Description/Characteristics/Orientation in Facility
- Facility/Hardware Operational Procedures Integration
- Hardware/Facility Structural Interface Requirements
- Hardware/Facility Power Interface Requirements
- Support Personnel Required for Testing
- Hardware Weight
- Hardware Volume/Dimensions
- Special Hardware/Facility Interface Qualification Requirements
- Facility and Support Equipment Maintainability
- Facility Manpower Support Requirements
- Facility Support Requirements (Video, Photography, etc.)
- Tool Requirements
- Facility and Support Equipment Reliability
- Facility Maintenance Costs
- Facility Operating Costs
- Facility Operational Procedures
- Facility Scheduling
- Hardware Scheduling
- Data Collection Capability
- Crewman/Facility Familiarization
- Communication Requirements
- Subject Safety
- EL/LSS Operational and Performance Characteristics
- Space Suit Operational and Performance Characteristics
- Crew/Cargo Transfer Systems Operational and Performance Characteristics
- Communication/Telemetry Systems Operational and Performance Characteristics
- Tools Operation and Performance Characteristics
- Man's Physiological Requirements
- Equipment Stress Areas (Vibration, Thermal, etc.)

TABLE 2-9: EVA Systems/Hardware Development Considerations (Cont'd.)

MISSION SUPPORT REQUIREMENTS: SIMULATION/TRAINING HARDWARE

- EVA Mission Definition
- Flight Hardware Operational Characteristics
- Total Simulation/Training Requirements
- Mockup Requirements
- Fidelity Requirements
- Development Scheduling
- Reliability
- Maintainability
- Operational Life
- Size
- External Volume
- Weight
- Transportability
- Safety
- Tool Interface Requirements
- Tool Requirements
- Hardware Operational Characteristics
- Required Illumination Levels
- Hardware Lighting Requirements
- Hardware Power Requirements
- Description/Characteristics/Orientation in Facility
- Facility Structural Interface Requirements
- Hardware/Facility Power Interface Requirements
- Training/Simulation Facility Selection

- Existing Qualified Facilities
- Hardware/Facility Flexibility
- Special Hardware/Facility Interface Design Requirements
- Special Hardware/Facility Interface Qualification Requirements
- Facility/Hardware Operational Procedures Integration
- Facility Scheduling
- Shelf-Item Stock Hardware Available
- Frequency of Use
- Number of Crewmen Required for Training
- Hardware Development Costs
- Special Equipment Production Costs
- Hardware Maintenance Costs
- Hardware Support Personnel

TABLE 2-9: EVA Systems/Hardware Development Considerations (Cont'd.)

MISSION SUPPORT REQUIREMENTS: SIMULATION/TRAINING FACILITIES

- EVA Mission Definition
- Existing Qualified Facilities
- Simulation/Training Mode Requirements ("0-g", etc.)
- Facility Environmental Fidelity
- Facility/Hardware Operational Procedures Integration
- Hardware Description/Characteristics/Orientation in Facility
- Hardware/Facility Structural Interface Requirements
- Hardware/Facility Power Interface Requirements
- System Support Personnel Required for Training
- Hardware Weight
- Hardware Volume/Dimension
- Special Facility/Hardware Interface Design Requirements
- Special Facility/Hardware Interface Qualification Requirements
- Facility and Support Equipment Maintainability
- Facility Operational Lighting Requirements
- Facility and Support Equipment Power Requirements
- Facility Manpower Support Requirements
- Facility Support Requirements (Video, Photography, etc.)
- Required Illumination Levels
- Tool Requirements
- Tool Interface Requirements
- Facility and Support Equipment Reliability

- Facility Development Costs
- Facility Maintenance Costs
- Facility Operating Costs
- New Facilities/Technology Cost
- Facility Preparation/Checkout Time
- Facility Operational Procedure
- Facility Scheduling
- Hardware Scheduling
- Data Collecting Capability
- Crewman/Facility Familiarization
- Communication Requirements
- Backup/Emergency Requirements
- Subject Safety
- Task Definition and Procedures
- Subject In-Suit Time Limits
- Frequency of Training Session
- Number of Crewmen Required for Training

TABLE 2-9: EVA Systems/Hardware Development Considerations (Cont'd.)

MISSION SUPPORT REQUIREMENTS: CREW/EQUIPMENT OPERATIONAL PROCEDURES DEVELOPMENT/VERIFICATION

- EVA Mission Definition
- Crewman EVA Function(s)
- Crewman Task/Event Definition
- EVA Worksite Description
- Crewman/Equipment Interface Requirements
- Equipment Operational Characteristics
- Total Number of Crewmen Required for EVA Support
- Number of Crewmen Required at Worksite
- Frequency of EVA Operations
- Duration of EVA Missions
- Type of EC/LSS Used
- EC/LSS Operational and Performance Characteristics
- Type of Space Suit Used
- Space Suit and Support Hardware Operational and Performance Characteristics
- Total Pressure Suit Anthropometrics
- Crewman Restraint Requirements
- Restraint System Operational Characteristics
- Spacecraft Atmospheric Pressure
- Spacecraft Atmospheric (One or Two Gas) System
- External/Internal Illumination Level
- Airlock Module Physical and Operational Characteristics
- Airlock Support Equipment Operational (Hatch, Control Panels, Pressurization/Depressurization)
- Spacecraft/EVA Equipment Interface Operations
- Crew and Cargo Transfer System Definition and Operation
- EC/LSS Backup System Operational Characteristics
- Number of Crewmen Required to Don/Doff Space Suit
- Number of Crewmen Required to Don/Doff EC/LSS
- Suit Donning Facilities Description
- Suit Drying and Maintenance Facilities Description
- EC/LSS Recharge and Maintenance Facilities Description
- Communications and Telemetry Systems Operational Characteristics
- Tool(s) Description and Operation
- Equipment/Hardware Stowage Requirements
- Cargo Mass Handling Limits
- Man's Physiological Requirements/Limitations
- Man's Psychological Considerations
- Man's Task Performance Capabilities in EVA
- Mobility Capabilities of Suited Crewman
- Visibility Capabilities of Suited Crewman
- Crewman Time Limits in EVA
- Crewman Safety Requirements
- Crewman Rescue Requirements
- Backup/Emergency System Operational and Performance Characteristics
- Total Simulation Requirements
- Required Simulation Modes (1-g, Water Immersion, Zero-g)
- Available Simulation Facilities
- Simulation Facility Description
- Simulation Facility Support Equipment
- Simulation Hardware/Mockup Fidelity
- Extent of Training Required

REFERENCES

2.1 NASA: Summary of Gemini Extravehicular Activity, NASA SP-149, Washington, D.C., 1967.

2.2 NASA: Gemini Summary Conference, NASA SP-138, Washington, D.C., 1967.

2.3 Manned Spacecraft Center: Apollo 9 Mission Report, MSC-PA-R-69-2, Houston, Tex., May 1969.

2.4 NASA: Apollo 15 Mission (AS-510) Post Launch Mission Operation Report No. 1, M-933-71-15, August 1971.

2.5 Martin Marietta Corp.: Skylab Operations Handbook, Contract No. NAS8-2400, Houston, Tex., July 19, 1971.

2.6 NASA: Reference Earth Orbital Research and Application Investigations (Blue Book), NHB-7150.1, January 15, 1971.

2.7 Martin Marietta Denver Division: Experiment Requirements Summary for Modular Space Station and Space Shuttle Orbital Applications and Requirements, Rev. 1, Subcontracts MDAC-WO-69-4-016 and MDAC-W-71-1-001, 1971.

2.8 General Dynamics: Research and Applications Module (RAM), Phase B Study, Contract No. NAS8-27539, August 28, 1971.

CHAPTER III

ORBITAL EVA EQUIPMENT CHARACTERISTICS

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

3.0 INTRODUCTION

The orbital EVA missions conducted on the Gemini and Apollo flights demonstrated that satisfactory task performance outside the spacecraft is basically dependent on three fundamental areas of procedural and technological development. These areas are (1) the EVA manipulative techniques employed by the crewman in order to accomplish a given function, (2) the ability to effect task planning and procedural development within man's orbital physiological and performance limitations, and, most important, (3) the development of hardware to properly support the crewman in the EVA environment. Analysis of the EVA problems encountered during the early Gemini missions led to corrective action in several areas. The resultant success of the later Gemini and Apollo orbital missions substantiate the three requirements designated above. The primary factors contributing to the successful orbital EVA of the later missions were careful EVA task planning, work rate limitations, proper training by means of high fidelity simulations, environmental control/life support systems of adequate capacity, and sufficient mobility and stabilization systems (refs. 3.1 and 3.2).

The development of EVA techniques and the need for systems capable of supporting relatively complex future EVA tasks lead immediately to the performance requirements of EVA hardware. If the hardware cannot properly support the crewman in the EVA environment, then the crewman cannot develop the requisite techniques for task performance. As future space missions become more ambitious, the crewman will be required to perform extravehicular activities which will not only enhance mission success but may be essential to mission completion. Currently anticipated earth orbital missions may involve spacecraft and experiment maintenance, repair, data retrieval, inspection, assembly, resupply, cargo transfer, rescue, and so forth. These operations depend largely on the adequacy of the crewman's support systems and hardware (ref. 3.3).

The future EVA function identification and manned EVA design/selection considerations introduced in the previous chapter were intended to present the reader with an overview of the numerous aspects of manned EVA. The next essential step in determining man's potential role in future EVA missions is to define the current technology status of operational EVA hardware systems and equipment and to delineate the status of ongoing hardware development programs.

The status of operational and developmental EVA systems is presented by specifying the physical, operational and performance characteristics of the major systems and subsystems supporting manned EVA. Emphasis is placed on the systems/hardware performance characteristics with cursory information concerning the physical and operational characteristics. Data

involving these areas are included only to assure understanding of the equipment performance characteristics. Amplification will be left to documentation specifically concerned with EVA hardware operation. The succeeding discussions will treat the following categories of EVA equipment:

- Environmental Control and Life Support Systems
- Crew Protective Systems (Space Suits)
- Airlock and Support Equipment
- Crew and Cargo Transfer Systems
- EVA Worksites, including Restraints
- External Lighting
- Communications and Telemetry Systems
- Data/Information Management Systems
- EVA Tools

3.1 ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS

3.1.1 Introduction

The basic life support system for the EVA space-suited crewman must be capable of meeting the following requirements:

- Pressurization and pressure control of the crewman's suit
- Provision for oxygen supply for respiration
- Removal of Carbon Dioxide (CO_2), odors, and other contaminants
- Provision for thermal control (temperature and humidity)

The environmental control hardware for EVA can range from totally self-contained units, carried with the crewman, to simple interface connections between the vehicle and the space suit by means of an umbilical. The environmental control and life support system (EC/LSS) hardware may be generally categorized into portable life support systems (PLSS) and vehicle-dependent systems. The Apollo backpack unit typifies the portable systems (Figure 3-1), whereas the Gemini umbilical EVA system represents a vehicle-dependent type (Figure 3-2). The chestpack shown in Figure 3-2 also contains the EVA contingency oxygen system. The size of the components for umbilical systems have been reduced for future orbital EVA missions from those of the early Gemini flights.

Generally, the umbilical EVA EC/LSS utilizes spacecraft oxygen and electrical power support. Electrical power is supplied for the operation of the caution and warning systems, pressure and temperature transducers, communication, bioinstrumentation, and panel lights. Umbilical systems for Skylab also contain space suit cooling water loops, which supply water to the crewman's liquid-cooled garment (LCG). Oxygen is provided by the spacecraft's high pressure gaseous oxygen system, regulated to approximately 120 psia and supplied to a space suit ventilation control module. Umbilical

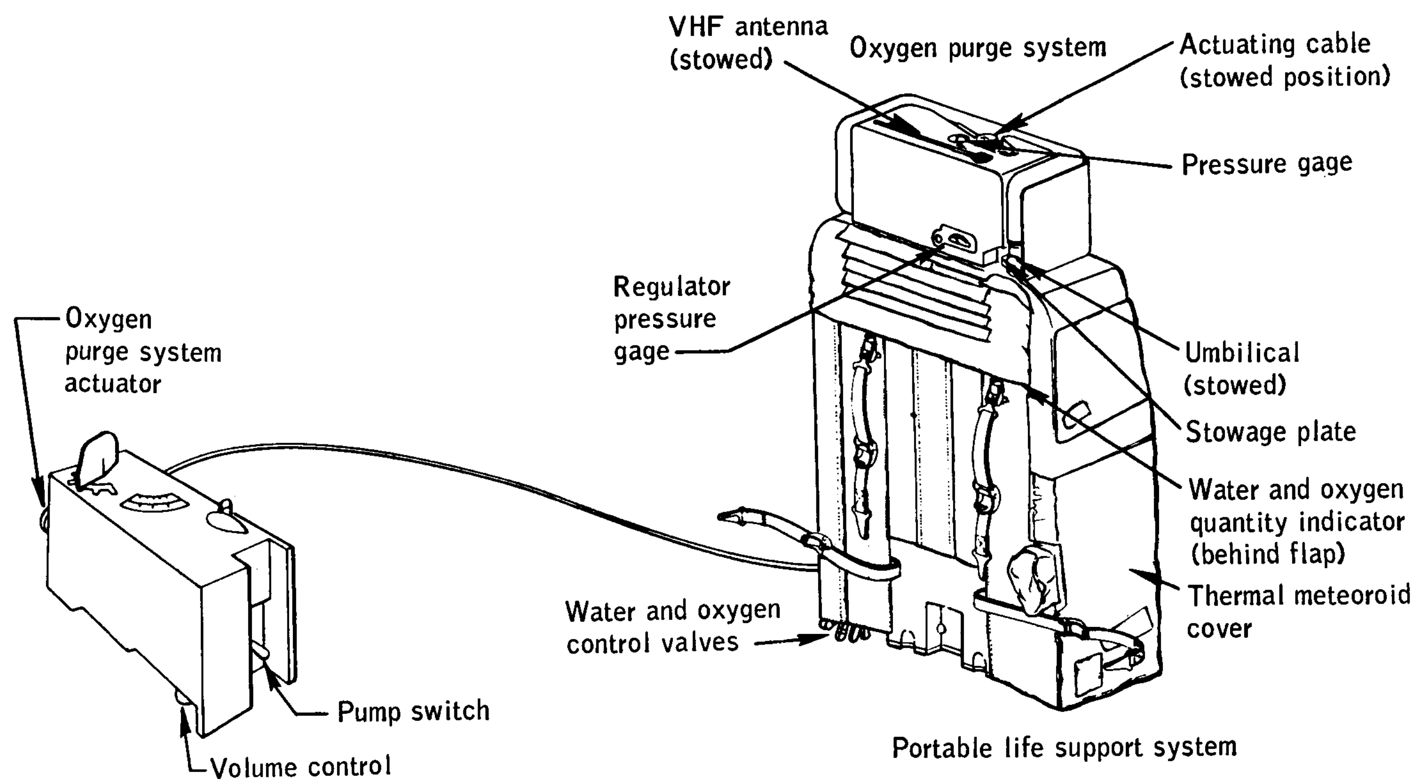


FIGURE 3-1: Apollo 9 Portable Life Support System

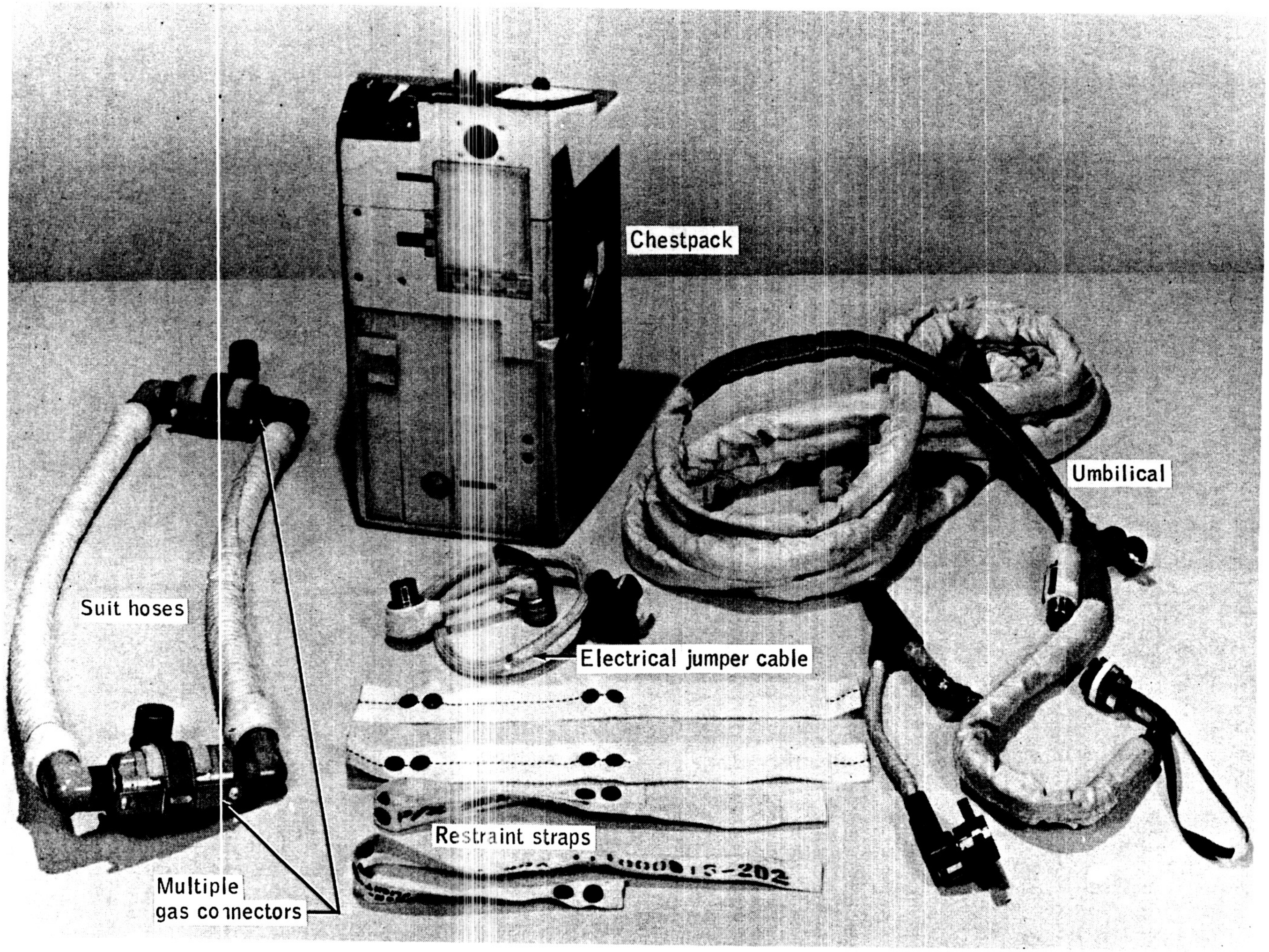


FIGURE 3-2: Umbilical Life Support System Components Used on Gemini IX-A Through XII

systems are of the open and semiopen ventilation types, and oxygen is lost to the space environment during EVA operations. Carbon dioxide, contaminant, and humidity control is accomplished by dumping space suit circulated oxygen into space. It is desirable in an open system to maintain the ventilation rate at the minimum level that provides adequate CO_2 and water vapor wash-out in order to conserve O_2. Based on previous orbital EVA experience, life support umbilicals should not exceed 60-75 feet in length due to the management, stowage, and possible entanglement problems.

The portable EVA life support systems were primarily designed for lunar surface operations but are equally applicable to orbital EVA. Portable systems designed to date have been of the type that make extensive use of expendables to accomplish all environmental control functions. Oxygen is supplied by high pressure bottles; CO_2 is removed by lithium hydroxide; heat is rejected by sublimation of stored water, and condensates are collected for humidity control. In general terms, the portable units are two-loop systems -- an oxygen circulating loop for thermal and composition control of the space suit atmosphere and a water loop for cooling through the LCG. To complete the total system, a power supply, communication/telemetry system, displays and related sensors, and switches and controls are normally included. Portable life support systems are favored where long-range orbital EVA operations (in excess of 60-75 ft.) are required because umbilical length would be excessive.

Self-contained oxygen systems for use in the event of primary life support system failure are normally provided during all EVAs in which the crewman completely egresses the vehicle. The systems serve as backup units when an umbilical or a portable primary system is used. The backup units are essentially oxygen purge systems with sufficient suit pressurization and flow capacity to the oronasal area to maintain CO_2 levels within physiologically tolerable limits. The various units were sized to provide emergency oxygen for nine minutes on the first Gemini EVA to in excess of thirty minutes on the later Gemini and the Apollo flights. Skylab contingency units are also sized for a thirty minute oxygen supply.

3.1.2 EC/LSS Characteristics

The following discussions concerning EC/LSS equipment characteristics will treat systems used on the early orbital missions, currently qualified systems, and promising systems in the advanced development stage. A summary of the EC/LSS used on the Gemini flights is presented to illustrate the criticality of sizing life support systems for the range of workloads expected and to familiarize the reader with evaluations of past orbital EVA systems.

The first manned EVA was conducted during the Gemini IV Program. The EC/LSS consisted of a small, chest-mounted ventilation control module which received oxygen through a 25 ft. umbilical from the spacecraft. The system was an open type and provided oxygen at the rate of 8.2 lbs./hr. for suit pressurization and crewman ventilation and cooling. The chest-mounted ventilation module contained an emergency oxygen supply sized for approximately nine minutes' operation. The ventilation control module weighed

approximately 7.75 pounds and was 250 in.^{3} in volume (ref. 3.4). At EVA termination, the crewman's metabolic rate and energy heat output was very high during hatch closing operations. During this activity, the crewman became overheated and exceeded the capacity of the ventilation control module. The crewman perspired heavily and experienced light visor fogging (ref. 3.2).

The second generation of EVAs (Gemini IX-A, XI and XII) was conducted with the Extravehicular Life Support System (ELSS), which, like its predecessor, was supplied oxygen through a 25 ft. umbilical from the spacecraft. (An Astronaut Maneuvering Unit carried aboard Gemini IX-A was a self-contained unit incorporating all systems necessary to support EVA operations.) The umbilical also supplied electrical power to the ELSS for nominal operation. This system operated semiopen-loop, dumping about 1/3 of the ejector pump circulated gas overboard for CO_2 control. The ELSS contained an evaporative heat exchanger (to cool and condense moisture from the ventilation gas), a warning system, and an emergency battery and oxygen supply for emergency operation. Two ventilation flow settings were available to permit metabolic heat rejection at high and moderate levels of activity. The suit ventilation flow rate associated with these settings were 5.1 lbs./hr. for metabolic rates up to 1400 Btu/hr. and 708 lbs./hr. for metabolic rates to about 2000 Btu/hr. The self-contained emergency provisions were sized for operation without the umbilical (independent of the spacecraft) for up to 33 minutes. The ELSS volume was 1350 in.^{3} and weighed 42 pounds (ref. 3.3). During the Gemini IX-A and XI EVA operations, the crewmen experienced fatigue and high energy expenditure in their attempt to maintain body positioning. The increased workload resulted in heavy perspiration and visor fogging (ref. 3.2).

During the Apollo 9 orbital EVA mission, a portable life support system (PLSS) with a secondary oxygen purge system (OPS) was used. This was the initial operation and evaluation of a primary portable life support system in the orbital environment. The PLSS (designated the -6 PLSS), with minor modifications, was used on the Apollo 11 lunar landing mission and later on the Apollo 12 and 14 missions. The -6 PLSS provided 3 hours operation at 1600 Btu/hr. and 4 hours at 1200 Btu/hr. with metabolic heat rejection by water circulation through an LCG (Liquid Cooled Garment) at 240 lbs./hr. Gas circulation was closed loop at 5.5 CFM and CO_2 scrubbing was by LiOH. The coolant temperature of the LCG could be varied from 45°F to 70°F by the crewman. The -6 PLSS contained an RF communications system for transmission of voice, biomedical, and system performance parameters. This system operated entirely independent of the spacecraft, but it did not provide the crewman with cooling until the cabin was depressurized to permit sublimator operation. The -6 PLSS volume is 5100 in.^{3}, weighs 84 pounds, and is rechargeable from spacecraft support systems (ref. 3.4). This life support system performed satisfactorily during the orbital qualification testing, and it provided adequate life support throughout the EVA missions. With the exception of minor equipment malfunctions, the -6 PLSS operations (both orbital and lunar) have fulfilled mission objectives.

The -7 PLSS (Figure 3-3), which is an extended-duration version of the -6 PLSS, is a currently qualified system for orbital EVA use. The -7 PLSS will be used through the Apollo 17 lunar surface missions, but it is not currently scheduled for orbital EVA operations. The Oxygen Purge System (OPS; see Figure 3-4) mounted on the PLSS is used in conjunction with the -7 PLSS as a contingency life system.

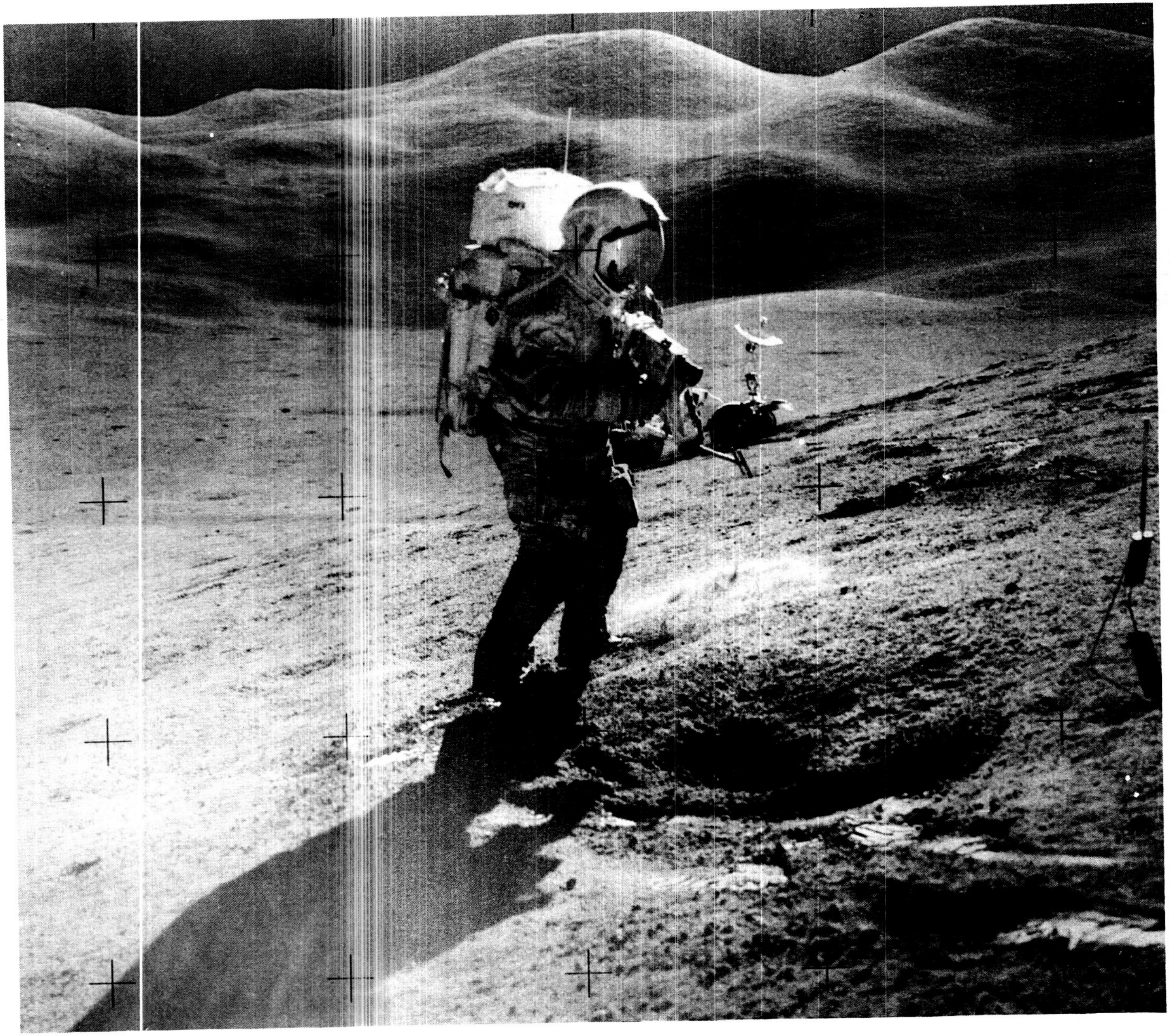


FIGURE 3-3: -7 PLSS Used During Apollo 15 Lunar Excursions

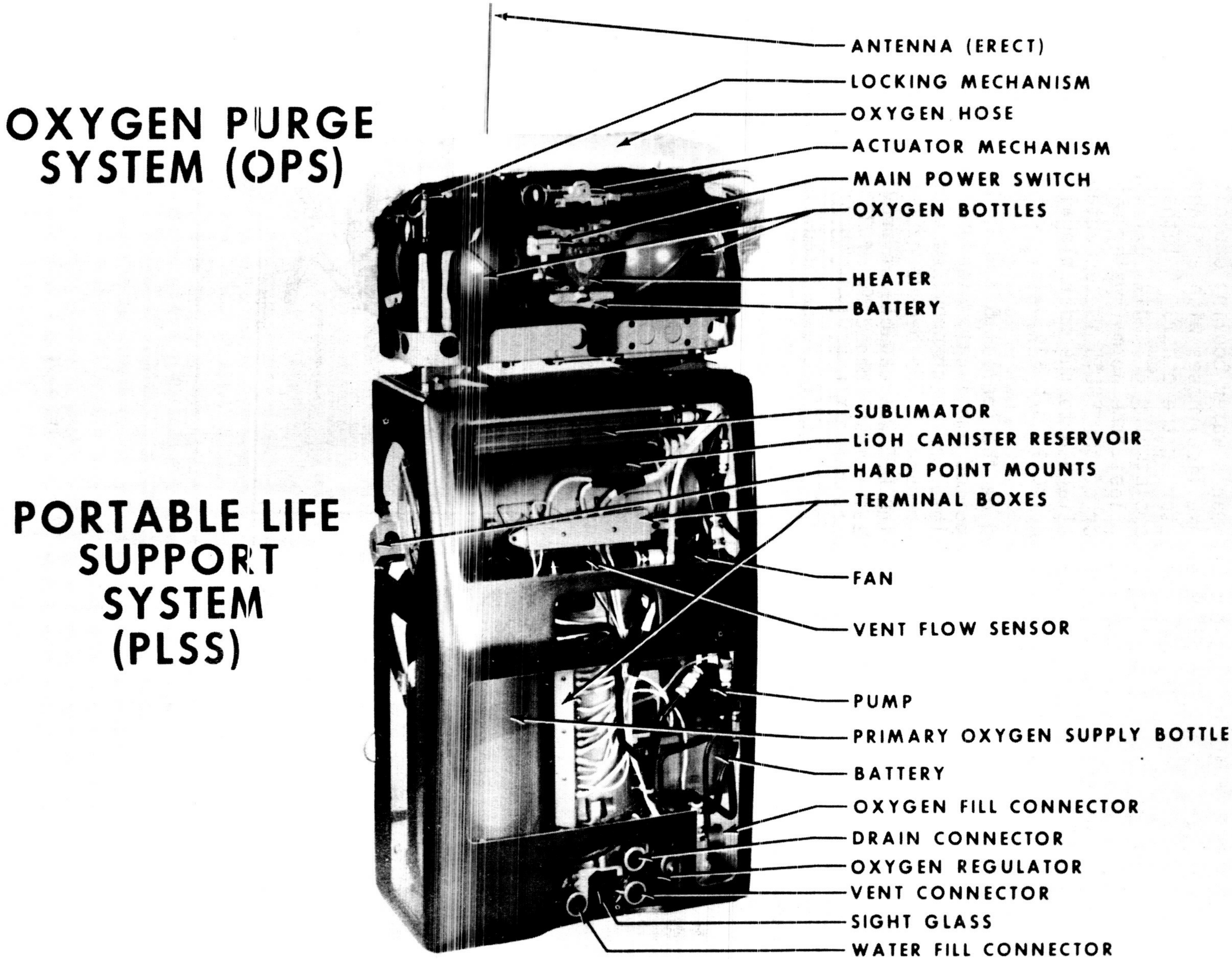


FIGURE 3-4: Oxygen Purge System - A Backup Life Support System (Shown with PLSS)

The primary performance characteristics, along with the physical and system operational characteristics, for the -7 PLSS and OPS are shown in Table 3-1. A Buddy Secondary Life Support System (BSLSS), shown in Figure 3-5, is used in the event that one crewman's water cooling capacity is lost. The BSLSS consists of a pair of water umbilical hoses with a standard connector on one end and a special divider connector at the other. A tether strap, two snap hooks, and an insulation sheath complete the assembly. If the water cooling capacity of one PLSS is impaired or lost, the normal water umbilical is disconnected, and the standard connector of the BSLSS is connected to the suit. The special divider connector is then attached to the operational PLSS, and the water flow is shared by two crewmen (refs. 3.5 and 3.7).

The prime life support system used on the Apollo 15 and 16 transearth EVA operations was a 25 ft. spacecraft supported umbilical. The umbilical supplied an oxygen flow rate of 10 to 12 lbs./hr. which provided 1200 to 1800 Btu/hr. heat removal capability to the crewman. The backup oxygen systems consisted of an OPS and purge valve. The OPS was capable of providing a flow rate of 8 lbs./hr. of O_2 with a heat removal capacity of 800 Btu/hr. The system would provide an oxygen supply for 0.5 hrs. (ref. 3.8). After completion of the transearth EVA, the OPS oxygen was exhausted into the spacecraft cabin to assist in repressurization.

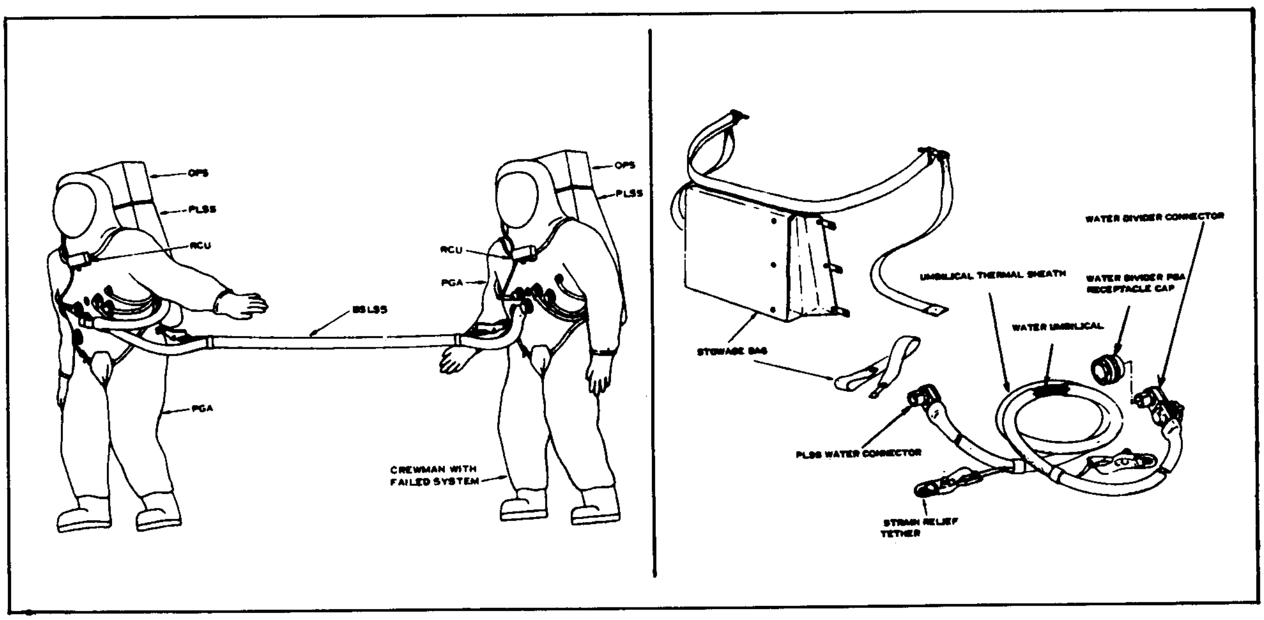


FIGURE 3-5: Buddy Secondary Life Support System

TABLE 3-1: Flight Qualified EVA Life Support Systems

EVA LIFE SUPPORT SYSTEM	MISSION USED ON OR DESIGNED/ RESEARCHED FOR	PHYSICAL CHARACTERISTICS WEIGHT (lbs)	PHYSICAL CHARACTERISTICS VOLUME (in^3)	PHYSICAL CHARACTERISTICS SIZE (LxWxD -in)	SYSTEM OPERATIONAL CHARACTERISTICS	SYSTEM PERFORMANCE CHARACTERISTICS: OXYGEN SYSTEM	METABOLIC CAPACITY	CARBON DIOXIDE	ELECTRICAL POWER	REMARKS
PRESSURE CONTROL UNIT--PCU (ASTRONAUT LIFE SUPPORT ASSEMBLY-ALSA)	Skylab	30.0 Net (Max.)	1147.5 (Max.)	18.2 x 9.7 x 6.[illegible]	OXYGEN • Gaseous O_2 supplied from OA* ECS. • Controls O_2 pressure and flow to PGA. • Pressure controlled by regulator #1, backup #2. • CSM/AM ECS allows control of O_2 temp. CO_2 • Open-loop ventilation dumps EVA O_2 and CO_2 to space. ODOR • Open-loop dumps odor, H_2O vapor, contaminants. COOLING • O_2 flow and liquid cooled garment. POWER • Spacecraft dependent.	FLOW • Normal 7.9 to 9.0 lb/hr. • Emer. 12.5 to 14.0 lb/hr. Press. to PGA 37 $^{+0.0}_{-0.0}$ Psia	CREWMAN • 700 to 1600 BTU/hr for 4 hrs. based on respiratory quotient of .85 • Failure of cooling H_2O gives 1000 BTU/hr. for 1.0 hr.	Open-type ventilation maintains a partial pressure of CO_2 below 7.5mm Hg in the oral-nasal area.	POWER • OA power supplied to PCU at 28 ± 4 vdc • PCU load - Caution & warning - Pressure transducer - Temp. transducer - Panel lights - OBS and Comm.	OXYGEN: MIL-O-27210 Type I INSULATIONS: Limits rate of heat loss or gain to + 240 or -200 BTU/hr.
LIFE SUPPORT UMBILICAL--LSU (ASTRONAUT LIFE SUPPORT ASSEMBLY-ALSA)	Skylab	56.0 Wet (Max. 50.0 Dry (Max.	—	60 ft. Long	• Supplies O_2, electrical power, communications, telemetry, water circulation and restraint tether. • Oxygen umbilical characteristics. - Operating temp. 40° to 90°F - Operating range. -200° to + 300°F. - Operating press. range 55 to 120 psia (max. 176.2). - Pressure drop (DP) 10 psid.	N/A	N/A	N/A	N/A	MATERIAL: Polyvinyl Chloride. H_2O umbilical characteristics • Max. pressure 28.5 (blk.) • Max. flow 250 lb/hr. • Min. flow 200 lb/hr. • Press. drop 3.0 psi
SECONDARY OXYGEN PACK--SOP (ASTRONAUT LIFE SUPPORT ASSEMBLY-ALSA)	Skylab	48.0 Wet	999.4 (Max.)	15.8 x 5.5 x 11.5	• Unit provides O_2 to PCU in event of OA ECS O_2 supply failure or O_2 umbilical failure. • Automatic flow in event of failure. • Tank pressure 6000 psi at 70°F.	FLOW • Normal 7.9 lb/hr for .5 hrs. • Emer. 13.1 lb/hr. for 18 min. usable O_2 3.95 lb.	CREWMAN • 700 BTU/hr. for 0.5 hrs. • 1600 BTU/hr. for TBD (respiratory quotient of .85)	Open-type ventilation maintains a partial pressure of CO_2 below 7.5mm Hg in the oral-nasal area.	N/A	CONTROLS • ON-OFF flow switch DISPLAYS • Storage pressure • Regulated supply • Pressure
PORTABLE LIFE SUPPORT SYSTEM--PLSS-7	Apollo	105	5100	26.0 x 17.8 x 10.5	• Self-contained system that provides O_2, H_2O circulation, communications and telemetry. • Remote control unit houses electrical controls, O_2 quantity indicator and OPS actuator. • O_2 storage tank - 1410 psia at 70°F. - 0° to 90°F operating temp.	FLOW • 0 to 3.8 lb/hr. at 3.75 to 4.05 psia O_2 flow.	CREWMAN • 1200 BTU/hr. for 6 hrs. • Short term 2000 BTU/hr.	Closed-loop ventilation using LiOH for CO_2 removal and charcoal for odor removal. Maintains CO_2 below 7.5mm Hg for 6 hrs. at 1200 BTU/hr.	POWER • Silver zinc battery • 7.85 hrs duration • 21.9 amp-hour min. cap. • Replaceable	• Expendables Depletion is rate sensitive. • 30 channel telemetry system • Audible and visual warning for low feedwater pressure, low O_2 flow, high O_2 flow and low PGA pressure.
OXYGEN PURGE SYSTEM-OPS	Apollo	42.0	1400	—	• OPS contains two spherical tanks holding 5.7 lbs. of O_2 at 5880 psia and 70°F. • Operating temp. -130° to + 130°F. • Operating press 0 to 6750 psia. • System contains manually operated shut-off valve and single-stage in-flow press. regulator.	FLOW • Normal 4.0 lb/hr. • High 8.0 lb/hr. Usable O_2 -5.8 lb.	(See O_2 system)	Open-type ventilation	N/A	• Normally mounted on top of PLSS, can be mounted on back of helmet or against abdomen.

* Abbreviations used in this Table are shown below.

ALSA	Astronaut Life Support Assembly	CSM	Command Service Module	mm HG	Millimeters of Mercury	OPS	Oxygen Purge System
AM	Airlock Module	Emer.	Emergency	N/A	Not Applicable	PCU	Pressure Control Unit
BTU	British Thermal Unit	ECS	Environmental Control System	O_2	Oxygen	PGA	Pressure Garment Assembly
CO_2	Carbon Dioxide	LiOH	Lithium Hydroxide	OA	Orbital Assembly	PLSS	Portable Life Support System
Comm.	Communications	LSS	Life Support System	OBS	Operational Bioinstrumentation System	TBD	To Be Determined

The Skylab orbital EVA missions will utilize an Astronaut Life Support Assembly (ALSA). The ALSA consists of three major components: (1) a Pressure Control Unit (PCU), Figûre 3-6; (2) a 60 ft. life support umbilical, Figure 3-7, and (3) a Secondary Oxygen Pack (SOP), Figure 3-8. The PCU is mounted on the front of the crewman's suit to provide controls and warning systems for oxygen and water supplied from the spacecraft by the umbilical. The SOP is attached to the crewman's left leg and provides emergency oxygen. The life support umbilical supplies oxygen, water and electrical power from the spacecraft systems. Although the ALSA is spacecraft dependent, it permits operation within a toxic or partially pressurized environment and can, therefore, be utilized as a contingency system or as a prime EVA life support system (ref. 3.10). The umbilical also serves as a restraint tether. The characteristics of the EC/LSS to be used during Skylab EVA missions are contained in Table 3-1. The EVA space suit configuration with the ASLA is shown in Figure 3-9.

A number of primary life support systems and backup or emergency units have been designed, developed and ground base tested for potential orbital and lunar applications. Development programs for certain systems have been temporarily discontinued. Others have been abandoned completely. A status and characteristics summary of the major systems to reach at least a prototype level of development are shown in Table 3-2. Most of these systems were developed during the 1967-69 period. Research and development programs for improved EVA life support system expendables, components and subsystems were also conducted during this time period. The program objectives were to develop systems that would provide high density O_2 storage, extended shelf life, reduced weight and volume, high heat load capability and simple recharge for future long duration EVA missions. These programs included research in the following areas (ref. 3.5):

- Chemical beds that can replace and improve upon the CO_2 scrubbing capacity of LiOH and provide O_2 for metabolic oxygen. Catalized Li_2O_2 testing has indicated that a smaller quantity of Li_2O_2 is required than LiOH for a specified CO_2 removal rate and provides sufficient O_2 to reduce the oxygen recharge requirements.

- Regenerable expendables for portable life support system applications. Programs include selection of promising concepts, feasibility testing, prototype development and testing, and flight hardware development and qualification by 1975.

- Integration of EVA life support system components into the pressure suit. This concept utilizes areas of the pressure suit for expendables, stowage, and system components to yield a reduction in the overall EVA system weight and volume.

- Evaporative Cooling Garment (ECG) to increase body heat rejection. The ECG increases the contact area between the crewman's skin and the transport fluid to remove metabolic heat from localized areas of large muscle mass and more total heat from the body.

- Sodium Chlorate ($NaCLO_3$) candles for prime and emergency portable life support system application. Work includes optimization of candle formulation, processing procedures and techniques, and the development of reliable ignitors.

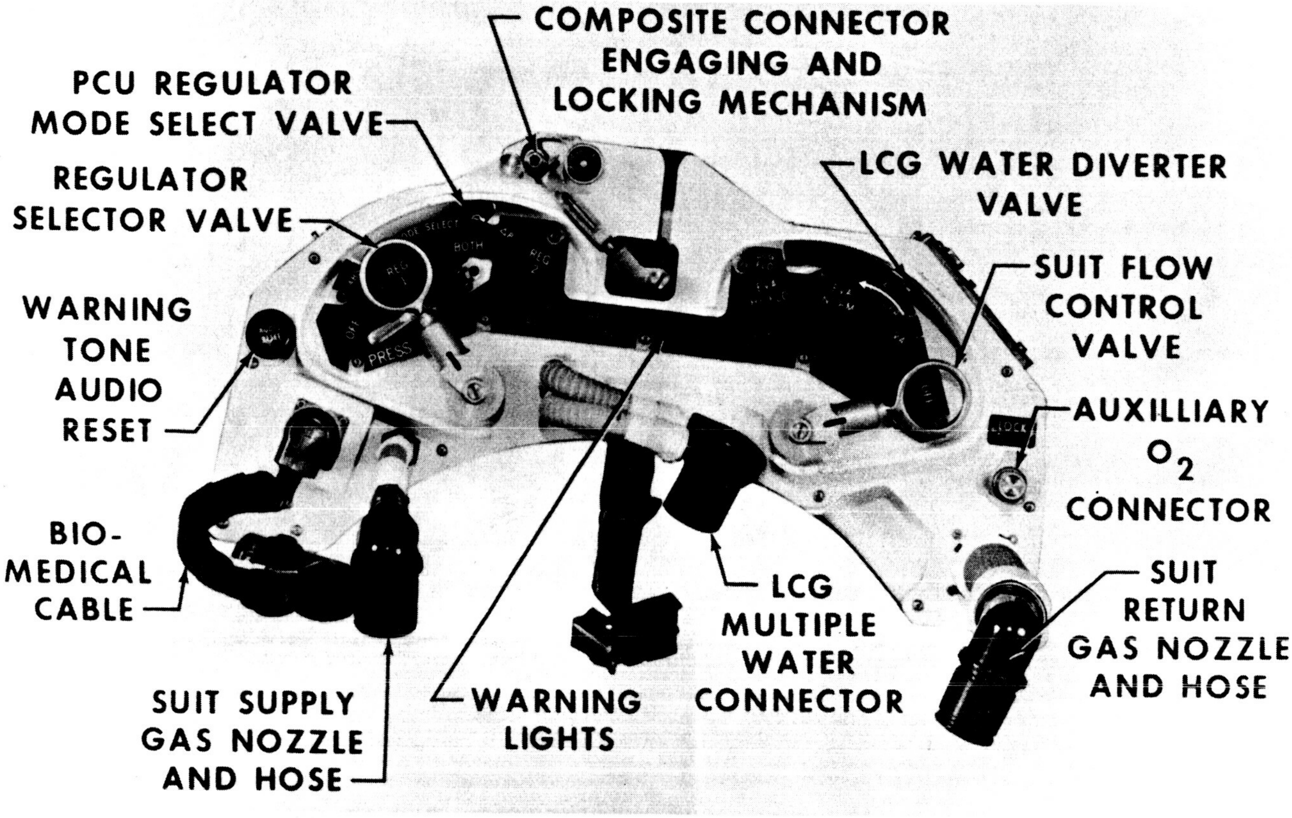


FIGURE 3-6: Skylab Pressure Control Unit (PCU)

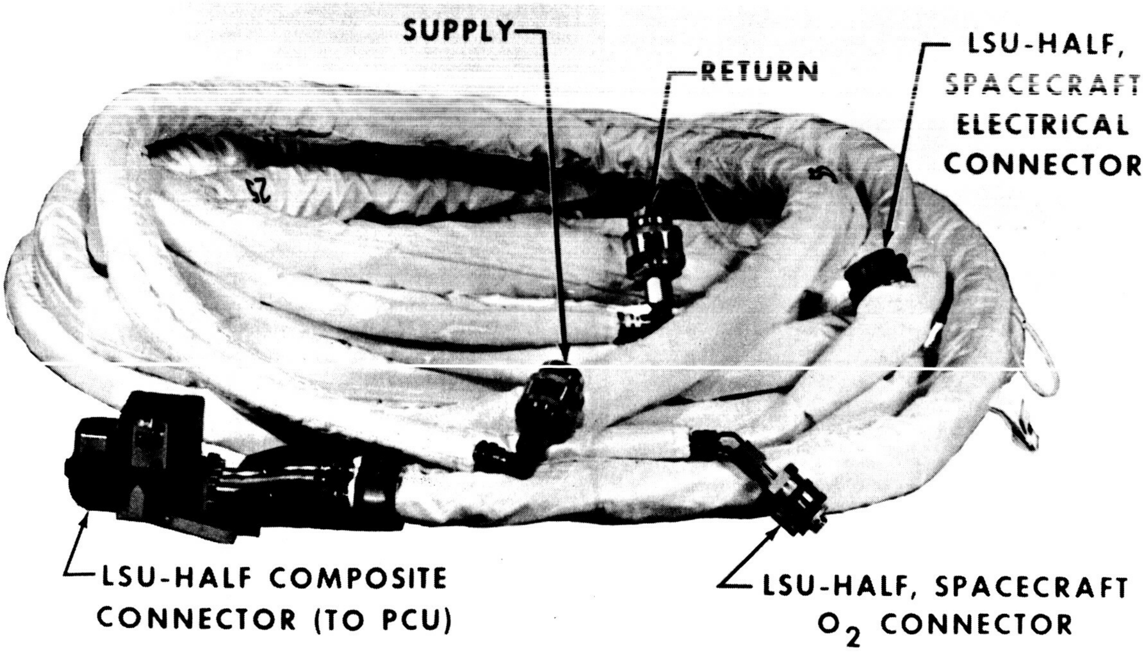


FIGURE 3-7: Skylab Life Support EVA Umbilical

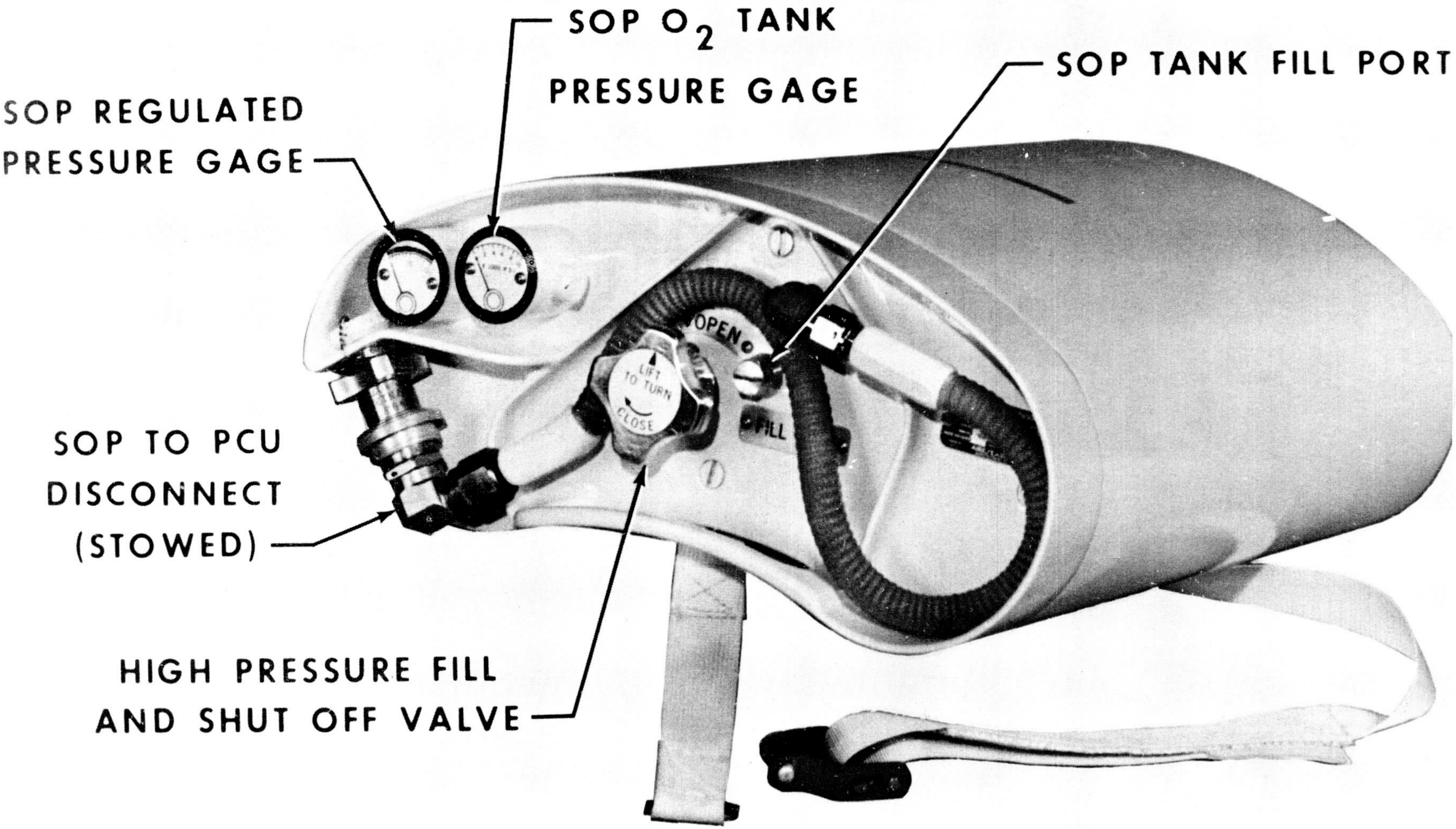


FIGURE 3-8: Skylab Secondary Oxygen Pack (SOP)

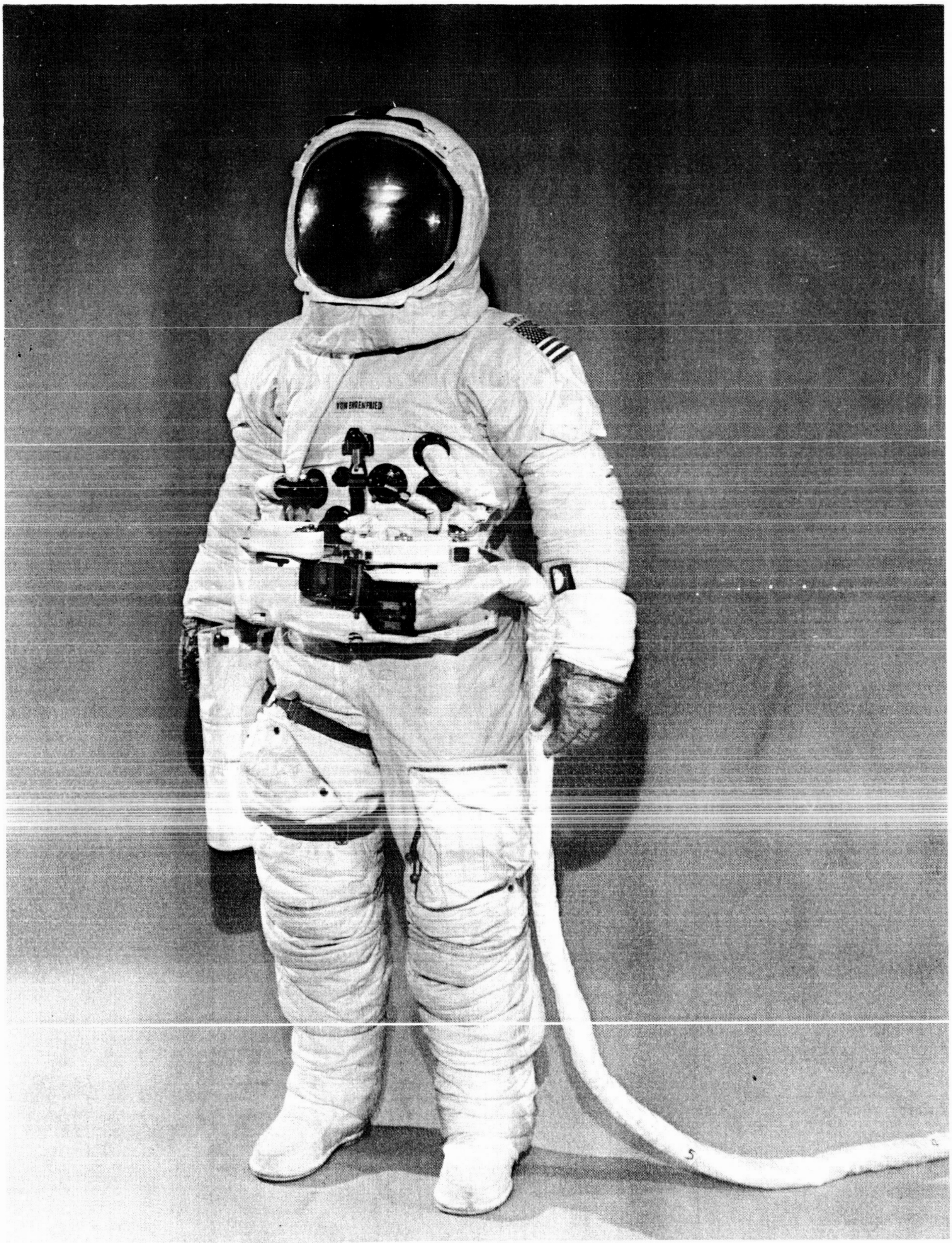


FIGURE 3-9: EVA Space Suit Configured with the ALSA

TABLE 3-2: EVA Life Support Systems Developed (Units Never Flown)

LIFE SUPPORT SYSTEM	GENERAL SYSTEM CHARACTERISTICS										
	SYSTEM STATUS	SYSTEM TYPE	WEIGHT (lbs)	VOLUME (in^3)	DIMENSIONS (LxWxH-in)	OXYGEN SUPPLY	METABOLIC CAPACITY (BTU/hr)	COOLING METHOD	COOLING FLOW RATE	MOUNTING LOCATION	REMARKS
PORTABLE ENVIRONMENTAL CONTROL SYSTEM (PECS)	No Present Work	• Portable • Self-Contained • Primary Life Support • Closed Loop	102	3560	26x6x16	Sodium Chlorate Candles	• 8000 BTU Total • 2000 BTU/hr. for 4 hrs. • 3500 BTU/hr. for 3.2 hrs.	Gaseous Flow Flow Liquid Cooling Garment (LCG)	-	Back	• O_2 supplied by decomposition of sodium chlorate candles. • Self-contained power supply or via umbilical. • 30 minutes emergency O_2 supply. • Contains liquid to liquid heat exchanger. • 250 BTU/hr. environmental heat load.
OPTIMIZED PORTABLE LIFE SUPPORT SYSTEM (OPLSS)	No Present Work	• Portable • Self-Contained • Primary Life Support	140	4700	-	Gaseous Oxygen	• 9600 BTU Total • 1600 BTU/hr. for 6 hrs.	Gaseous Flow	-	Back	• Removable expendables module. • Redundant 1.5 hrs. emergency capacity. • Provisions for umbilical expendables supply from spacecraft. • Umbilical interface for IV operation.
SECONDARY LIFE SUPPORT SYSTEM (SLSS)	No Present Work	• Portable • Backup Life Support	65-70	1400	-	Gaseous Oxygen	• 3200 BTU Total • 1600 BTU/hr. for 2 hrs.	Gaseous Flow LCG	5.5 acfm 240 lb/hr	Back	• Water recharge required following the first 1.5 hrs. of operation. • Uses liquid cooling garment loop.
CONTINGENCY TRANSFER SYSTEM (CTS)	–	• Portable • Backup Life Support	16.5	600	-	Gaseous Oxygen	• 1500 BTU Total • 2000 + BTU/hr. for .75 hr.	Gaseous Flow LCG	1.25 acfm 240 lb/hr	Back	• Utilizes an aluminum, dip-brazen sublimator, pneumatic pump, and in-suit breathing vent. The vent reduces the O_2 flow required to the oronasal area for CO_2 control.

- Systems to eliminate water recharge requirements for portable life support systems. Concepts include vapor absorption heat rejection systems and fusable salt heat sinks.

A NASA funded EVA life support system research and development program, the Advanced Extravehicular Protective System (AEPS), was conducted (1971-2) by Hamilton Standard (Division of United Aircraft). The objective of the AEPS study was to provide a meaningful appraisal of various regenerable and partially regenerable portable life support system concepts for EVA use in the 1980's and to identify required new technology areas. The basic descriptions provided by the NASA for an orbital AEPS system stated:

> The AEPS shall be a portable system capable of supplying the life support functions of pressurization, ventilation, breathing oxygen supply, contaminant control, humidity control, and thermal control. The AEPS shall be a mission regenerable/rechargeable system and/or shall be capable of operating off a vehicle umbilical. (ref. 3.11)

The general conclusions and recommendations of the AEPS study were as follows:

Conclusions

- An AEPS configuration, by incorporating a regenerable CO_2 control subsystem and a thermal control subsystem and by utilizing a minimum of expendables, dramatically decreases the vehicle penalty associated with present configurations (such as the Apollo EMU PLSS) and can be designed to be within an acceptable AEPS volume and weight range.

- CO_2 reduction and oxygen reclamation within the AEPS is not competitive because of the resultant excessive weight and volume of the subsystems required to perform these functions.

- CO_2 reduction and oxygen reclamation, within the parent vehicle, of the CO_2 removed by the AEPS CO_2 control subsystem is only competitive when there are three or more parent vehicle resupply periods. (ref. 3.11)

Recommendations

- Thermal Control

  - Thermal Storage - Investigate and develop a thermal storage material(s) whose heat of fusion exceeds 300 Btu/lb. One such candidate material, PH_4Cl, has already been identified and analytically evaluated during conduction of the AEPS study.

  - Radiation - Investigate and develop radiator surface coatings and treatments to optimize performance and

minimize potential surface degradation. In addition, deploy a lightweight, deployable radiator concept.

- CO_2 Control

  - Develop a solid regenerable CO_2 sorbent that provides the performance, regeneration and life characteristics required for AEPS type applications. Two candidate families of solid regenerable sorbents -- metallic oxides and solid amines -- have already been identified and evaluated during conduct of the AEPS study.

- O_2 Supply

  - Develop a high cyclic life (1000 cycles)/high pressure (6000 psi nominal) O_2 supply subsystem that minimizes EVA equipment volume and meets life support requirements for AEPS type applications. (ref. 3.11)

3.1.3 EVA Life Support System Design/Selection Guidelines

Since operations performed outside the spacecraft involve additional risks to the crewman, it is mandatory that the EVA life support systems be designed to perform safely and reliably. The system designers and fabricators and also the personnel specifying systems for use on future missions must recognize the critical nature of the hardware. Preliminary, general guidelines that should be helpful in the design, development, and selection of an EVA life support system are presented below. Designers should be certain that these EVA life support system guidelines are considered (ref. 3.5).

3.1.3.1 Primary Life Support Systems

(1) Minimum attention should be required by the suited crewman to assure that the system is performing properly.

(2) Caution and warning systems should be designed to provide only those cues that are meaningful and helpful to the crewman in detecting and correcting malfunctions.

(3) The types and characteristics of auditory and warning devices must provide the discrimination necessary under all operating conditions.

(4) Caution and warning signals are deployed in the spacecraft in order that an EVA equipment systems assessment can be made by onboard spacecraft personnel and ground control.

(5) Emergency controls should be designed to be readily visible and readily accessible to the crewman.

(6) Replacement of filters/canisters must be accomplished readily in all environments, and, if replacement is done under vacuum conditions, it cannot compromise crew safety in any way.

(7) The range of gas inlet temperatures must be in agreement with specified exposure times for heat and cold.

(8) Ducts or duct connections should not emit odors or toxic fumes when subjected to operating temperatures.

(9) Materials selected for use in the life support system will exhibit minimum ignition propagation, smoke, or toxic outgassing characteristics under the most hazardous anticipated environments.

(10) Consideration must be made for providing adequate body cooling during EVA preparation periods and EVA postpreparation times.

(11) If the primary system fails and backup systems are available which require electrical power, the backup power should be supplied from a completely independent source.

(12) Adequate provisions for the storage, protection, and accessibility of the equipment and supplies must be provided.

(13) All electrical systems should be labeled, interlocked, isolated, or otherwise designed to minimize electrical shock.

(14) Actuating controls are so designed that they can be readily operated by the EVA suited crewman.

(15) CO_2 readout capability should be provided for onboard spacecraft monitors and/or ground control.

(16) Donning, doffing and servicing procedures should be provided in an area adjacent to the particular activity. Visual aids should be used to clarify operations.

(17) The primary system should be designed to minimize the effects of a nauseated crewman and the attendant effects.

(18) Biomedical instrumentation should be so designed that it limits the current flow to the crewman's body to no more than one milliamp under all operational or failed conditions.

(19) Checkout devices should not require interpretation. They should normally be of the GO - NO GO type.

(20) Sufficient controls and instrumentation are to be provided to permit checking out of those critical components, i.e., heaters, regulators, caution and warning systems, etc., where practical.

(21) Life support and thermal control subsystems must be designed with sufficient capacity to handle the maximum and minimum heat loads to meet established respiration and pressure requirements for the mission timeline involved.

(22) Component and total system design should be as simple as possible for the task it will perform.

(23) Expendable replacement units should be designed to ensure that position-sensitive components can be installed only in their proper orientation.

(24) The design of the system or subsystem incorporating redundancies should include a means of verifying satisfactory operation of each redundant path at any time it is determined that the system or subsystems require testing.

(25) Failure in any portion of the system must not cause or create additional or cumulative hazards.

(26) Engineering mockups should be used to determine the design safety aspects of the equipment, i.e., define optimum locations for access to critical controls.

3.1.3.2 Backup Life Support Systems

The backup life support systems should be designed to include the following:

(1) The system must allow for crew rescue throughout the EVA profile.

(2) Adequate oxygen must be provided to permit the crewman to return to the spacecraft from any EVA area in the mission profile.

(3) In deriving the oxygen requirements, consideration must be given to the limited cooling capability of backup systems.

(4) The oxygen flow path in the primary system should include flow restriction to minimize flow into the pressure suit to that of the relief capability of the suit relief valve.

(5) Preferably, the backup systems should be designed to eliminate all single point failures.

(6) Redundant methods should be utilized to overcome the effects of both a failed open regulator and a failed closed regulator.

(7) Past experience indicates that backup systems have been utilized as prime systems; therefore, they should provide adequate safety margins.

3.1.3.3 Life Support Controls and Connectors

(1) Control placement and accessibility should be determined by criticality and utilization frequency of the control.

(2) All controls must be designed to prevent inadvertent actuation.

(3) All connectors must be color coded. No two connectors shall be of the same color.

(4) Alignment marks must be provided on all keyed connectors.

(5) All connections affecting pressure integrity must have redundant locking devices which operate sequentially and may be visually verified.

(6) All connectors interfacing with life support systems must have the capability of providing an operationally acceptable method of vacuum transfers.

(7) All control positions should be verifiable without requiring recycling.

(8) All emergency controls operations should be ambidextrous.

(9) Control actuations must be conducive to suit mobility.

(10) System operations should require a minimum of the crewman's attention and control.

3.1.3.4 Caution and Warning Instrumentation

(1) Malfunctions or conditions which affect crewman safety or mission management must be displayed.

(2) All primary, backup, and emergency consumables should be instrumented to provide direct indications to the crewman of the amounts remaining.

(3) The crewman should not be required to perform switching functions to determine systems status.

(4) Each warning of a system malfunction should have a distinguishable feature for rapid identification of the individual malfunction.

(5) All warnings should be reusable and should be automatically reset when the anomaly is corrected.

(6) All warnings should be designed to provide an operational verification check prior to commitment to a vacuum environment.

(7) All warning indications should employ a test verification feature.

(8) Visual indication must be easily visible and readable in all environments.

(9) A disable/reset feature should be incorporated into multiple input warning systems in the event of a fail-on-input condition.

(10) Warning for low consumable levels should be selected to allow sufficient time for corrective action without dependence on the emergency system.

(11) All instrumentation should provide positive and direct indication of systems operation.

(12) Life support hardware should include sufficient telemetry to detect systems degradation and real-time consumable management to advise the crewman of potential problems and permit adjustments to the mission plan.

(13) All critical control positions should not be dependent on crew reporting.

3.2 CREW PROTECTIVE SYSTEMS (SPACE SUITS)

3.2.1 Introduction

In the development of early pressure suit assemblies, primary emphasis was placed on pressure and thermal protection, while functional mobility was classified as a secondary consideration. This was evident during the Gemini Program. For example, the basic Gemini EVA suit (G-IVC) was initially designed for intravehicular (IV) use. The suit consisted of a multilayer fabric system comprised of a comfort liner, gas bladder, structural restraint, and outer protective layer. A gas distribution system inside the suit directed oxygen flow to the helmet area for metabolic use and to the body extremities for thermal control. For EVA use, the basic suit was modified by adding the following equipment:

- EV cover layer to provide thermal and micrometeoroid protection
- EV gloves to reduce conductive heat transfer
- Low emittance coating on the exterior and interior surfaces of the helmet visor to minimize radiant heat loss, plus back reflectance coatings
- Helmet sun visor to attenuate solar illumination

This basic suit, with minor modifications, was used throughout the remainder of the Gemini Program.

During and at the close of the program, it was concluded that some of the major problems encountered during Gemini EVA were due to limitations in the mobility of the space suit. Since the suits had been designed primarily for IVA, the neutral position was a sitting configuration with the arms positioned in such a way as to enable easy access to the Gemini flight controls. Whenever a crew member moved within the suit, he had to overcome the forces which tended to return the suit to this neutral position. These forces were significant when the arms were raised above shoulder level. Thus, the Gemini astronaut

could not perform sustained work below the waist or above the shoulder level. As a result of the neutral position inherent in the suit, fatigue was significant whenever a "non-neutral" position was required and held for some time. It was recommended that for future applications priority should be given to improving the mobility of space suits, especially arm and glove mobility (ref. 3.12).

Present space suit technology can be divided into two distinct classifications: (1) existing systems that have been used on previous missions and are still considered nonobsolete, and (2) advanced systems that are in various stages of development. The specific suits per classification are as follows:

- Existing EVA Systems
    - Apollo Extravehicular Mobility Units (Apollo EMU)
    - Skylab EMU
- Advanced EVA Systems
    - Advanced Extravehicular Suits (AES)
    - Hard Suits

The following paragraphs present a brief description of each of the above suits, giving particular attention to the suits' design, application, and orbital EVA configuration. It should be pointed out that most of the development in the area of advanced suits has been minimized except for the AES.

3.2.2 Existing EVA Systems

3.2.2.1 Apollo EMU

The A-7L and the A-7L-B pressure suits were the primary pressure garment assemblies used during the Apollo Program. The A-7L suit (an anthropomorphic ensemble incorporating molded convolute joints for shoulder, hip, knee, wrist, elbow, and ankle mobility) was worn as the prime IV and EV suit beginning with the Apollo 9 flight and continuating through the Apollo 14 flight. The A-7L EV configuration suit was also worn by the Command Module Pilot on Apollo 15 and subsequent Apollo flights. At present, the A-7L suit has not been specified for additional flights. The A-7L basic suit and associated equipment used on Apollo is shown in Figure 3-10.

The A-7L-B suit is an A-7L that has been modified in order to provide increased waist and neck mobility and improved arm and shoulder mobility. In external appearance, the A-7L and the A-7L-B are similar. The A-7L-B suit was first used during the Apollo 15 lunar EVA. It was also used on Apollo 16 and is currently designated as the lunar surface suit for the Apollo 17 mission.

The A-7L/A-7L-B orbital and lunar configurations include the following equipment:

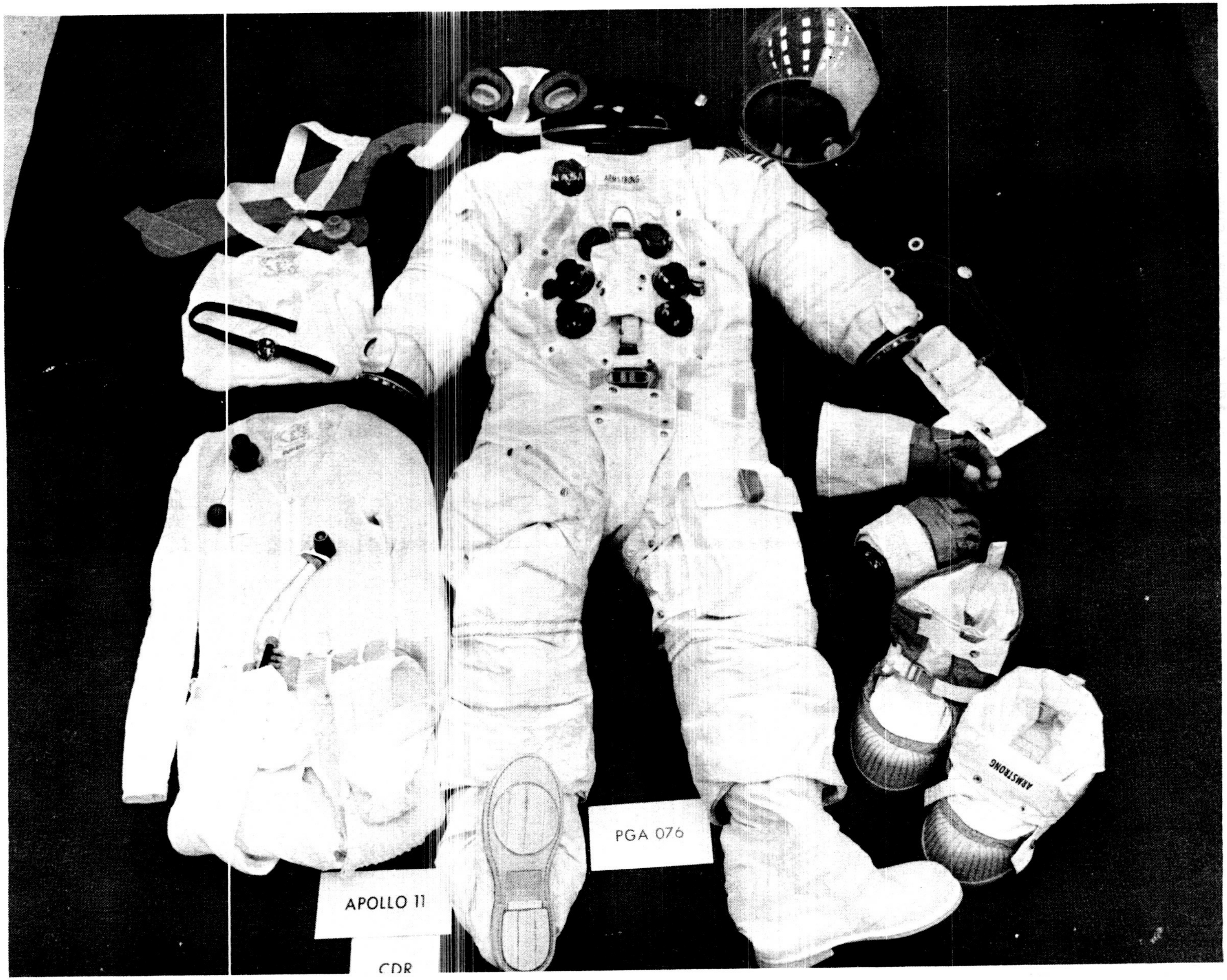


FIGURE 3-10: Apollo (A-7L) Space Suit

- Pressure Garment Assembly (PGA) with Integrated Thermal Micrometeoroid Garment (ITMG)
- EV Visor Assembly (EVVA) - Apollo 9 Orbital
- Constant Wear Garment (CWG)
- Oxygen Purge System (OPS)
- Environmental Control/Life Support System
  - Orbital: Life Support Umbilical (LSU)
  - Lunar: Portable Life Support System (PLSS)
- Urine Collection Transfer Assembly (UCTA)
- Communication Carrier Assembly (CCA)
- Lunar Extravehicular Visor Assembly (LEVA)
- Fecal Containment Subsystem (FCS)
- EV Gloves
- In-suit drinking device
- Bioinstrumentation system: Bioharness
- Lunar Boots: Lunar Configuration
- Electrical Harness
- Radiation Dosimeter
- Liquid Cooled Garment (LCG): Lunar Configuration

3.2.2.2 Skylab EMU

The Skylab Extravehicular Mobility Unit is the basic A-7L-B pressure garment assembly. The Skylab EMU orbital configuration, Figure 3-11, includes the following equipment (refs. 3.10 and 3.13).

- Pressure Garment Assembly (PGA) with Integrated Thermal Micrometeoroid Garment (ITMG)
- Liquid Cooling Garment (LCG)
- Pressure Control Unit (PCU)
- Life Support Umbilical (LSU)

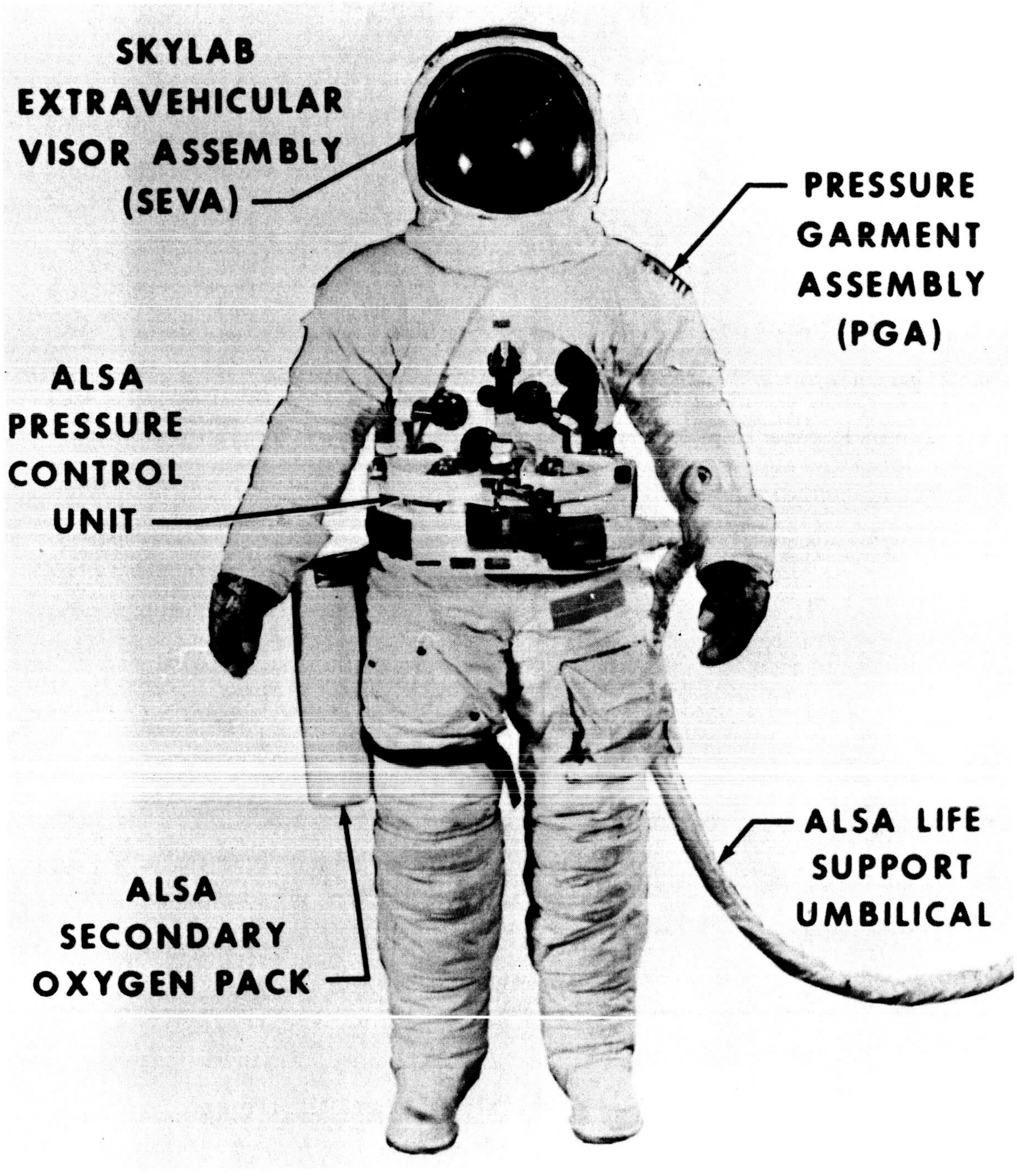


FIGURE 3-11: Skylab Extravehicular Mobility Unit (EMU)

- Secondary Oxygen Pack (SOP)
- Constant Wear Garment (CWG)
- Skylab Extravehicular Visor Assembly (SEVA)
- Urine Collection Transfer Assembly (UCTA)
- Fecal Containment Subsystem (FCS)
- Communication Carrier Assembly (CCA)
- EV Gloves
- Bioinstrumentation System
- Suit Electrical Harness
- Radiation Dosimeter (active on leg; passive on watchband)

3.2.3 Advanced EVA Systems

3.2.3.1 Advanced Extravehicular Suit (AES)

The AES assembly utilizes a near constant volume joint system for shoulder, elbow, waist, hip, knee, and ankle mobility (see Figure 3-12). This type of joint system provides maximum mobility with a minimum amount of metabolic expenditure. The AES can be used with the following hardware to make up an orbital extravehicular mobility unit:

- Liquid Cooling Garment (LCG)
- Integrated Thermal Micrometeoroid Garment (ITMG)
- Extravehicular Visor Assembly
- EV Gloves
- Communication Carrier Assembly (CCA)
- Fecal Containment Subsystem (FCS)
- Urine Collection Transfer Assembly (UCTA)
- Suit Electrical Harness
- Bioinstrumentation System
- Radiation Dosimeter
- Life Support System

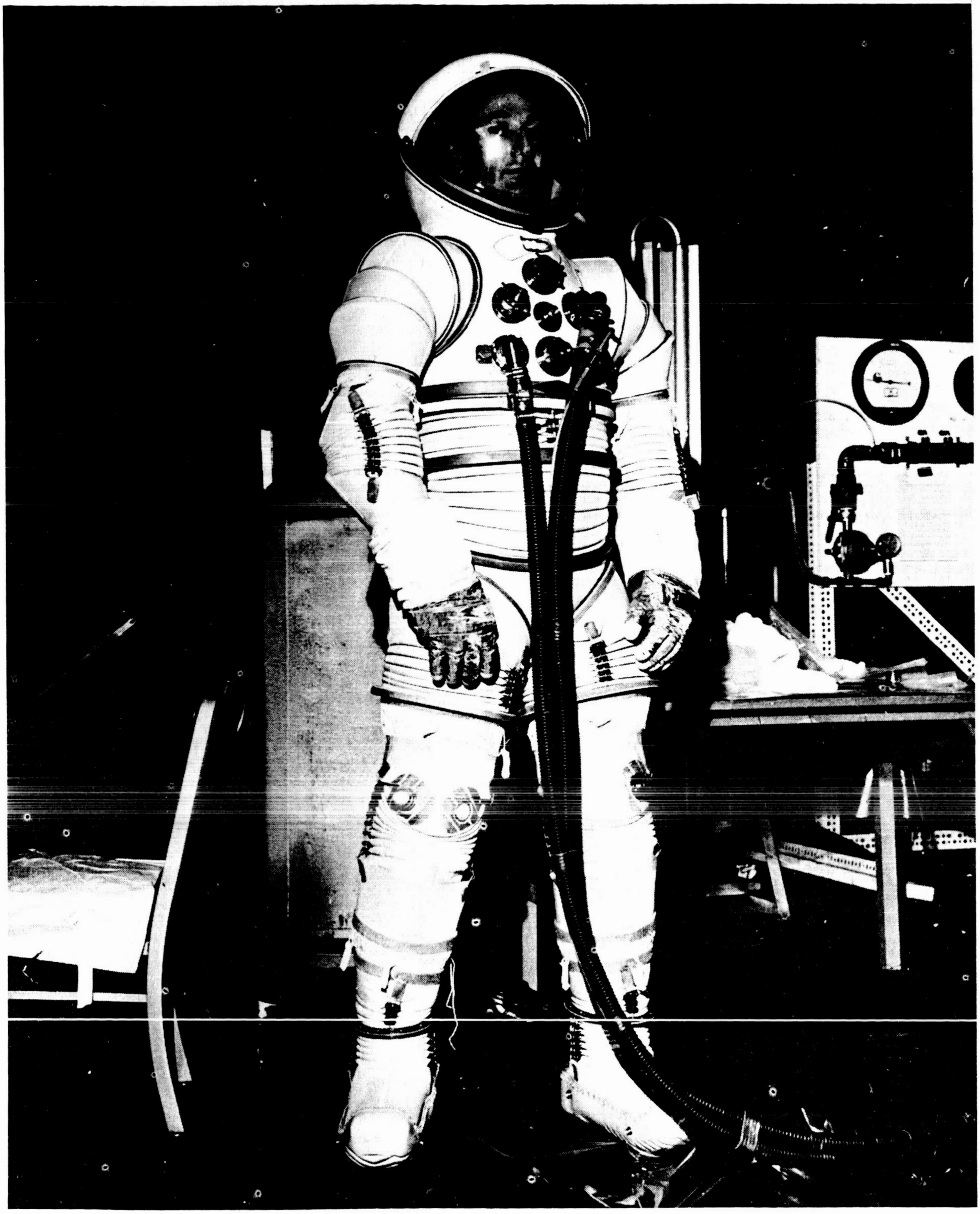


FIGURE 3-12: Advanced Extravehicular Suit (AES)

Parallel AES prequalification programs were awarded to both AiResearch and Litton Industries. During a seven-month program period, four prototypes of the AES were developed. Although the suit was originally baselined for the later Apollo missions, the following factors indicated that the metabolic rate reductions obtained using constant volume suits were of little importance:

- Increased mobility of A-7L-B
- Data obtained from Apollo XI Mission
- Increased capacity of Portable Life Support Systems (PLSS)

The above factors have contributed to a decreased emphasis on the AES development program (ref. 3.14).

3.2.3.2 Hard Suits

Perhaps the best examples of the hard suit concept development are the Litton RX-5 and the Ames AX-2 suits. These suits were developed primarily for lunar EVA operations.

The RX-5 utilizes near constant volume joint systems for shoulder, elbow, waist, hip, knee, and ankle mobility (see Figure 3-13). The basic hard suit structure is a composition layup of thin aluminum sheets faced with a fiberglass honeycomb and covered by a sheet layer of fiberglass. For thermal protection, a lightweight multilayer for superinsulation is incorporated as an integral part of the basic suit structure. The total weight of the RX-5, including the integral thermal and micrometeoroid protection, is approximately 67 pounds. The basic hard suit structure lends itself to the incorporation of portable life support system components to make a totally integral suit/life support system.

The Ames hard suit was developed using a rigid structure similar to the RX-type hard suits. In the Ames hard suit, however, a series of rotary bearings arranged in a "stovepipe" fashion is utilized for the prime shoulder, elbow, hip, knee, and ankle mobility joint systems. In combination with the rotary bearings in the hip and knee areas, a series of metal bellows is used for joint mobility. The metal bellows are the prime mobility system for the waist joint. The primary purpose of AX-2 suit development was to investigate the feasibility of the "stovepipe" joint and metal bellows for mobility systems.

The same factors contributing to the decreased emphasis on AES development have also contributed to the lesser emphasis now placed on hard suit development programs. A brief history of hard suit development is contained in Appendix A.

3.2.3.3. Integrated Life Support Systems

A recent Air Force study investigated the possibility of developing an Integrated Maneuvering Life Support System (IMLSS). This effort was intended to integrate a cold-gas maneuvering system into existing integrated EVA space suit/life support system design.

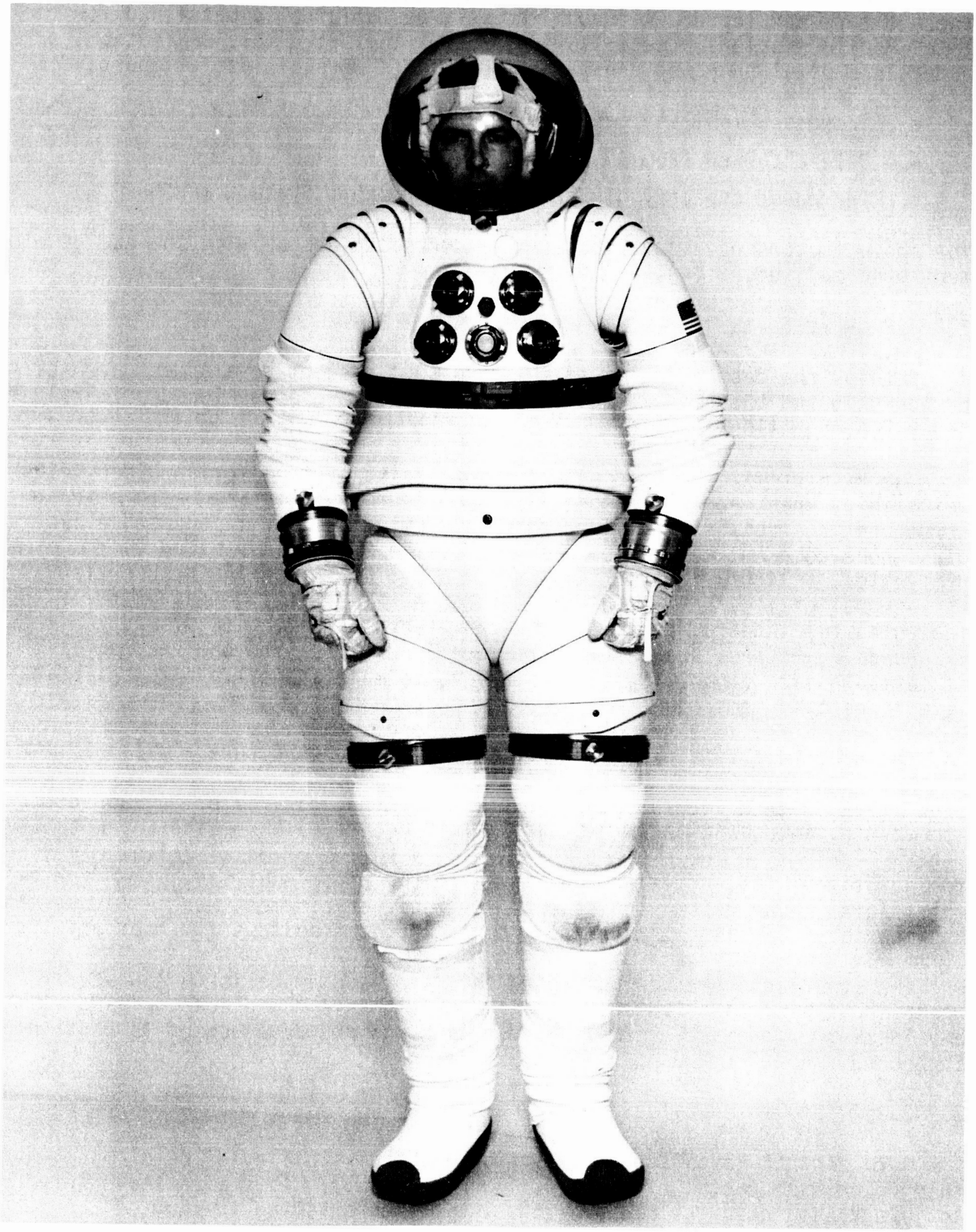


FIGURE 3-13: Hard Suit (RX-5)

The basic configuration of the IMLSS is shown in Figure 3-14. The addition of the cold-gas maneuvering system to the existing suit life support system design produced an advanced personnel protection system capable of sustaining totally independent extravehicular operation. The system provides environment protection, life support, and maneuvering, which, combined with unaided expendables recharge, affords extravehicular mission durations limited only by the crewman's endurance rather than by hardware design.

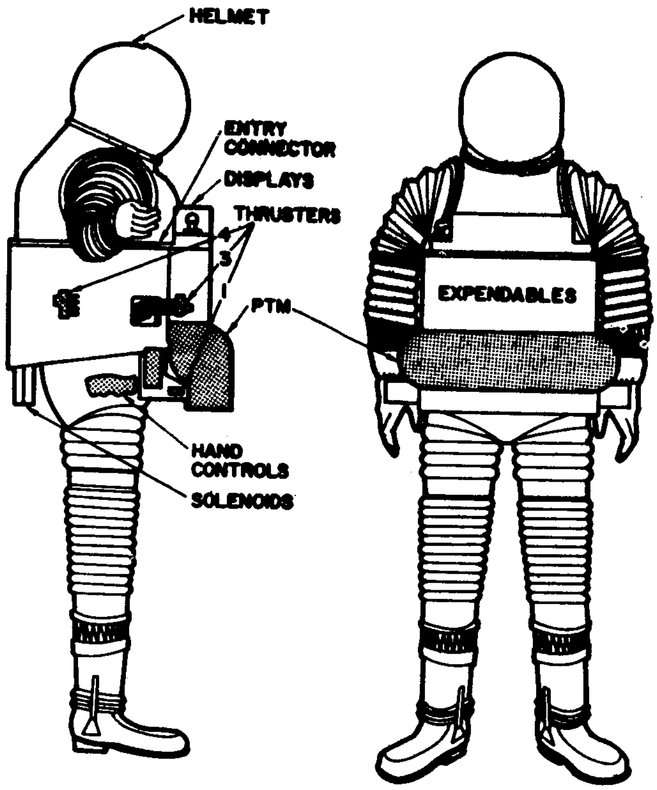


FIGURE 3-14: IMLSS Standup Configuration

A mockup with hard torso and soft arms and legs was evaluated on an air-bearing platform. The evaluations revealed that the IMLSS was superior to the add-on systems of the Apollo flights. Don/doff time and total stowage volume is less than that for equivalent separate functional units. Additionally, it was concluded that the grouping and location of controls and displays on the IMLSS was better than a more posterior position (ref. 3.15).

3.2.4 Comparison of Crew Protective Systems

Although the crew protective system provides a relatively comfortable environment for the EVA astronaut, it is also the major constraint on his ability to perform mission functions. Since this system directly affects man's performance capability, it is necessary to consider the system parameters (Chapter II) and characteristics in order to make a proper selection.

Tables 3-3 through 3-5 present a comparison of the physical, operational, and performance characteristics of the A-7L, the A-7L-B, and the Advanced Extravehicular Suit (AES) systems. The majority of the data presented within these tables were derived from Master End Item Specifications (refs. 3.16 through 3.19). Complete performance data were not available on each of the suits, and there may be minor data inconsistencies within the tables given here. If so, they are the result of conflicting data in the available documentation.

3.2.5 Comparison of Crew Protective Subsystems

In addition to the physical, operational, and performance characteristics of the above suits, descriptions and characteristics are provided on the following major A-7L, A-7L-B, and AES subsystems:

- EV Gloves
- Helmets
- Extravehicular Visor Assembly
- Integrated Thermal Micrometeoroid Garment (ITMG)
- Liquid Cooling Garment (LCG)
- Communication and Telemetry Systems

The majority of the data presented in the subsection were derived from Master End Item Specifications.

3.2.5.1 EV Gloves

- A-7L - The A-7L EV glove is a modified glove called the TMG Pressure Glove Assembly, onto which a thermal insulating cover is secured. The EV glove shell assembly is multilayered and similar in construction to the ITMG. In the palm and inner finger area, a woven metal (chromel-R) fabric provides resistance to abrasion and fire. The metal fabric is coated with a silicone dispersion compound to improve antislip characteristics. The outer cover is conformal and does not appreciably restrict dexterity. The glove is designed to maintain hand temperature within a range of 60° to 103°F. Orbital EVA specifications for the A-7L glove require the capability to grasp a one inch diameter rod (temperatures ranging from 250° to -150°F) with medium firm grip for 90 seconds. Cable restraints are incorporated into the glove design to limit extension during pressurization.

- A-7L-B - The A-7L-B glove is made similar to that of the A-7L. However, the following improvements have been incorporated (ref. 3.20):

    - improved donning/doffing by the enlarging of the wrist disconnects and convolutes

TABLE 3-3: Physical Characteristics of Selected Pressure Suits

PHYSICAL CHARACTERISTICS	UNITS	SPACE SUIT			REMARKS
		A7L	A7L–B	AES	
WEIGHT					
• Total	lbs.	-	-	67.41	
• Torso Limb Assembly, Integrated	lbs.	41.43	48.5	33.60	
• Helmet	lbs.	3.00	2.86	2.50	
• EV Gloves	lbs.	2.5	3.2	3.20	
• Bioinstrumentation Harness	lbs.	.25	.25	.25	
• Electrical Harness	lbs.	.54	.54	.50	
• Integrated Thermal Micrometeoroid Garment	lbs.	-	-	15.00	
• Extravehicular Visor Assembly (Lunar)	lbs.	4.4	4.4	4.00	
• Bioinstrumentation Belt	lbs.		1.10	1.10	
• Fecal Containment Subsystem	lbs.	.50	.50	.50	
• Urine Collection Transfer Assembly	lbs.	.53	.53	.53	
• Liquid Cooling Garment	lbs.		5.0(wet)	4.60(wet)	
• Communication Carrier	lbs.	5.0(wet)	1.63	1.63	
• Constant Wear Garment	lbs.		.8		
SUIT VOLUME					
• Volume	$ft.^3$	4.7	4.7		±10
• Free Volume	$ft.^3$	2.2	2.2		±5%
• Stowage Volume	$ft.^3$			7.0	Maximum
ENVELOPE AND CONFIGURATION					
• Across Shoulders	in.	26	26	23	
• Across Elbows	in.	28	28	25	
• Across Knees	in.	18	18	18	

TABLE 3-4: Operational Characteristics of Selected Pressure Suits

OPERATIONAL CHARACTERISTICS	UNITS	SPACE SUITS			REMARKS
		A7L	A7L-B	AES	
LIFE					
• Design Life					
• Useful Life	years	-	3		
• Shelf Life	years	3-4	2-3	5-6	
• Operational Life (Pressure)	hrs.	99.5	189	179	
• Operational Life (Vent)	hrs.	110	187	247	
PRESSURES					
• Operating Pressure	psig	3.75	3.75	5.00/3.75*	±0.25
• Proof Pressure	psig	8.00	8.00	10.00	
• Burst Pressure	psig	10.00	10.00	15.00	
• Structural Test Pressure	psig	6.00	6.00	6.00	
• Pressure Gauge Range	psig	2.5-6	2.5-6	2.5-6	
• Pressure Gauge Proof	psig	0-20	0-20	0-20	
• Pressure Gauge Accuracy	psi	±0.15	±0.15	±0.15	
• Pressure Relief Valve					
- Cracking Pressure	psig	4.8-5.5	5.0-5.75	4.4-5.5	
- Cracked Flow Rate	lbs/hr.	3.6±.2	12.2	3.6	
- Seal Pressure	psig	4.8	4.6	4.4	
• Pressure Drop					
- 6.0 CFM Flow @ 3.9 psia/O_2	in. H_2O	1.8	1.8	1.8	
- 12.0 CFM Flow @ Vent	in. H_2O		-		
- 12.0 CFM Flow @ 3.5 psia/O_2	in. H_2O	4.7	4.7		

*When operating at 5 psi, the AES Pressure Relief Valve is blocked.

TABLE 3-4: Operational Characteristics of Selected Pressure Suits (Cont'd.)

OPERATIONAL CHARACTERISTICS	UNITS	SPACE SUITS			REMARKS
		A7L	A7L-B	AES	
LEAKAGE RATES					
• Contingency Operating Mode	scc/min	360	360	1000	
• Normal Operating Mode	scc/min	180	180	200	
• - Pressure Relief Valve	scc/min	-	-	-	
- Helmet	scc/min	15	15	-	
- Glove	scc/min	10	10	-	
CONNECTOR & OPERATIONAL FORCES					
• Electrical Connectors	lbs.	15	15	15	
• Gas Connectors	lbs.	20	20	20	
• Liquid Connectors	lbs.	20	20	5	
• Glove Connection	lbs.	15	15	15	
• Ventilation Diverter Valve Operation	lbs.	10	10	10	
VENTILATION					
• Operational Flow Rates	cmf	6-12	6-12	6-12	
• Ventilative Metabolic Cooling	Btu/scfm	800/12	800/12	-	Maximum
THERMAL					
• Ambient Operational Temperature Range	°F	-290/+300	-290/+300	-290/+250	
• Heat Loss to Environment	Btu/hr.	350	350	-	
• Heat Gain from Environment	Btu/hr.	250	250	-	
• Ventilative Cooling Temperature Range	°F	35-85	35-85	-	

TABLE 3-5: Performance Characteristics of Selected Pressure Suits

PERFORMANCE CHARACTERISTICS	RANGE OF MOVEMENT (DEGREES)			MAX TORQUE GOALS (FOOT-POUNDS)			REMARKS
	A7L	A7L-B	AES	A7L	A7L-B	AES	
NECK MOBILITY							
• Flexion Forward	120	45			1*		Torques listed are those required to move the suit through the specified angles. They are a function of the suit and not the strength of the crewman in the suit.
• Flexion Backward	120	45			1		
• Flexion Right	30	55			1		
• Flexion Left	30	55			1		
• Rotation Right	110	110			1		
• Rotation Left	110	110			1		
SHOULDER MOBILITY						**	
• Adduction	35	70	33		1	.875	
• Abduction	125	90	132		1	.875	
• Shoulder Movement Lateral - Medial	145	130	200		1	.875	
• Flexion	170	160	165		1	1.3	
• Extension	47	40	40		1	1.3	
• Rotation (X-Z Plane) Down-Up		125	180		1	0.1	
• Lateral Rotation	35	110	20		1	0.1	
• Medial Rotation	95		130		1	0.1	
ELBOW MOBILITY							
• Flexion - Extension	137	130	150		1	.833	
FOREARM MOBILITY							
• Supination (Palms Up)	90	95	120		2.5	.14	
• Pronation (Palms Down)	75	95	75		2.5	.14	

*Design goals only

**Measured values at 5.7 psig

TABLE 3-5: Performance Characteristics of Selected Pressure Suits (Cont'd.)

PERFORMANCE CHARACTERISTICS	RANGE OF MOVEMENT (DEGREES)			MAX TORQUE GOALS (FOOT-POUNDS)			REMARKS
	A7L	A7L-B	AES	A7L	A7L-B	AES	
WRIST MOBILITY							
• Extension (Forward)	56	40			* 2.5		
• Flexion (Backward)	57	35			2.5		
• Flexion (Adduction)	42	70			2.5		
• Extension (Abduction)	30	45			2.5		
TRUNK-TORSO MOBILITY							
• Trunk Rotation (Left-Right)	5	5			2	**	
• Torso Flexion (Left-Right)	5	60	20		2	2	
• Torso Flexion (Forward)	90	110	123		2	4	
• Torso Flexion (Backward)	5	25	21		2	4	
HIP MOBILITY							
• Abduction (Leg Straight)	45	20	35		2	2	
• Adduction (Knee Bent)	30	5	45		2	1.5	
• Abduction (Knee Bent)	35	15	45		2	1.5	
• Rotation (Sitting):Lateral	30	20			2		
• Rotation (Sitting): Medial	30	20			2		
• Flexion	115	70	140		2	1.63	
• Extension	20	0			2		
KNEE MOBILITY							
• Flexion (Standing)	110	105	140		1	.655	
• Rotation (Medial)	15	0			1		
• Rotation (Lateral)	15	15			1		
• Flexion (Kneeling)	140	150	170		1	.655	

TABLE 3-5: Performance Characteristics of Selected Pressure Suits (Cont'd.)

PERFORMANCE CHARACTERISTICS	RANGE OF MOVEMENT (DEGREES)			MAX TORQUE GOALS (FOOT-POUNDS)			REMARKS
	A7L	A7L-B	AES	A7L	A7L-B	AES	
ANKLE MOBILITY					*	**	
• Extension	40	50	45		3	1.5	
• Flexion	35	30	45		3	1.5	
• Abduction	25	20	25		3	1.5	
• Adduction	25	20	25		3	1.5	

*Design goals only **Measured values at 5.7 psig

- improved dexterity by the addition of curved fingers with thumb extensions and custom fitted external palm restraints

The EV glove is designed to maintain hand temperature within the range of 60° to 103°F during all extravehicular activity. Orbital EVA specifications for the A-7L-B glove require the capability to grasp a 1.25 inch diameter rod (temperature ranging from 250° to -250°F) with a loading of 2.0 psi for a period of 3 minutes. See Table 3-6 for the specification performance criteria of the A-7L-B glove.

- AES - The torso limb assembly was developed to interface, without interference, with government furnished EV pressure gloves P/N A7L-203025-11 and -12, which are the standard A-7L gloves.

Table 3-7 compares the mobility/dexterity characteristics of the A-7L, A-7L-B, and the AES gloves, insofar as documentation is available. Weight, leakage rates, and connection force information can be found in Tables 3-3 through 3-5.

3.2.5.2 Helmets

Generally speaking, the helmets are constructed of clear bubble-shaped lexan that has been bonded to a machined and anodized aluminum ring. The astronaut's head is free to move within the confines of the helmet, but his vision is limited by the location of the torso neckring and by mobility restrictions which limit rotation and elevation of his head. The critical area of vision corresponds to the normal field of vision, head fixed and eyes fixed in the primary position. The normal field of vision is defined to be at least the following, as measured from a reference point shown in Figure 3-15:

- Temporal -90°
- Superior Temporal -62°
- Superior 85°
- Inferior Temporal -85°
- Inferior 70°

As indicated, the visor is transparent and of good optical quality. The critical area is as free as possible of visible stria, cloudiness and other imperfections. It is specified that no imperfection should produce diffraction patterns and that the viewing area should be polished and specularly reflecting. Imperfections should not exceed the following (ref. 3.20):

- four in the viewing area
- one imperfection per square inch
- 0.03 inch diameter
- lint inclusions not exceeding 3/16 inches

TABLE 3-6: Specified Performance Criteria for the A-7L-B Glove

Movements or Operations	Performance Criteria
• Palmar	- Write legibly with pencil - Operate .375 inch dia. rotary knob - Utilize small screwdriver
• Tip Prehension	- Pick up small objects such as: Small screws Small rocks
• Lateral Prehension	- Operate 2 and 3 positions Toggle switches: Vertically Horizontally
• Grasp	- Use a screwdriver - Use pliers - Use crescent wrench - Use socket wrench
• Finger: Pushbutton Ops.	- Operate pushbutton within panel of pushbuttons
• Finger: Pulling Ops.	- Operate T-handle control - Operate D-handle control - Operate ring handle control
• Thumb	- Operate thumbwheel
• Hand Rotation	- Operate discrete position rotary switch
• Wrist Movements	- Move wrist side to side while opening and closing fingers - Move wrist up and down while opening and closing fingers
• Whole Hand Movement	- Hold hand at any desired position

TABLE 3-7: Glove Mobility of Selected Pressure Suits

TORQUING CAPABILITY	UNITS	OBJECT SIZE			FORCE (INCH-POUNDS)		
		A-7L	A-7L-B	AES	A-7L	A-7L-B	AES
• Fingertip	in./dia.	INFORMATION NOT AVAILABLE					
• Finger Curl Around	in./dia.						
• Screwdriver	in./long						
- Pronation							
- Supination							
• Ball	in./dia.						
- Pronation							
- Supination							
• Knob							
- Pronation							
- Supination							

PARAMETER	% OF NUDE HAND CAPABILITY			REMARKS
	A-7L	A-7L-B	AES	
• Dexterity	INFORMATION NOT AVAILABLE			
- Pick up 1/4" pins: right hand				
left hand				
both hands				
- Pick up 1/2" pins: right hand				
left hand				
both hands				
• Activation Time				
- Knobs				
- Push buttons				
- Toggles				

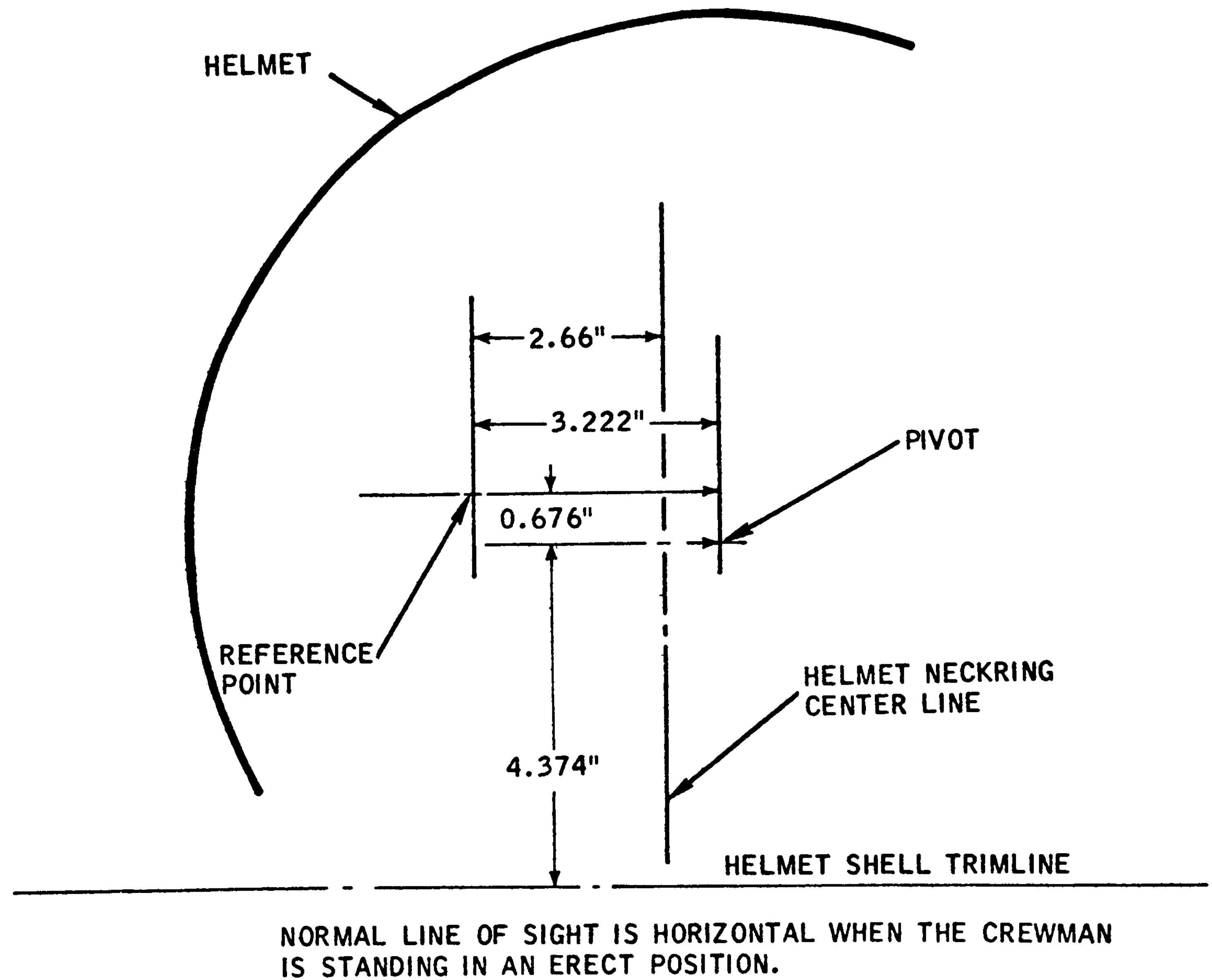


FIGURE 3-15: Helmet Reference Points for Areas of Vision

The spectral transmittance of the critical viewing area should conform to the following:

- Ultraviolet — 2000-3000 Å, minimum
- Luminous — 4000-7000 Å, 80%

The following helmet information can be found in Tables 3-4 through 3-6:

- Weight
- Leakage Rate
- Connector Force
- Visibility

3.2.5.3 Visor Assemblies - EVVA and SEVA

When the crewman is in the extravehicular environment, the EVVA or SEVA (Skylab) is worn over the PGA helmet to provide visual, thermal, impact and micrometeoroid protection. The EVVA and SEVA generally consist of the following components, enabling the crewman to maintain a comfortable level of light for optimum visibility:

- Formed Head Enclosure
- Thermal-Micrometeoroid Cover
- Protective Visor
- Sun Visor
- Left Glare Shade
- Right Glare Shade

The general EVVA requirements for each visor configuration are contained in Table 3-8 (ref. 3.13 and 3.21). Visor assemblies are shown in Figures 3-16 (EVVA) and 3-17 (SEVA).

TABLE 3-8: EVVA Optical Characteristics

	HELMET	PROTECTIVE VISOR	SUN VISOR	BLINDERS
Spectral Transmittance:				
Ultraviolet (2000-3000 Å)	Min.	0.1%	N/A	None
Luminous (4000-7000 A)	>80%	>60%	16±4%	None
Solar Reflectance	N/A	Max.	>30%	100%
Emittance	N/A	<20%	<10%	0

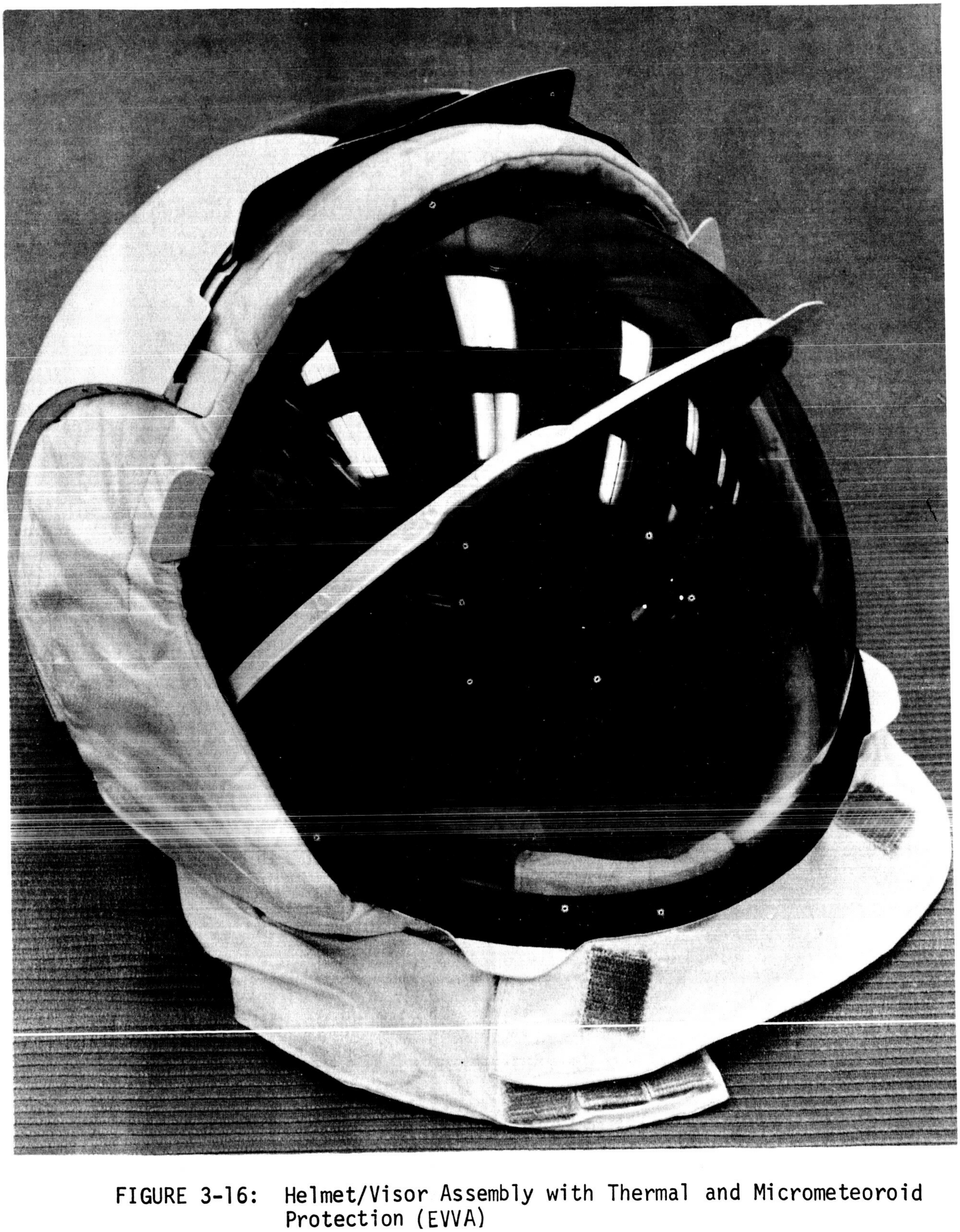


FIGURE 3-16: Helmet/Visor Assembly with Thermal and Micrometeoroid Protection (EVVA)

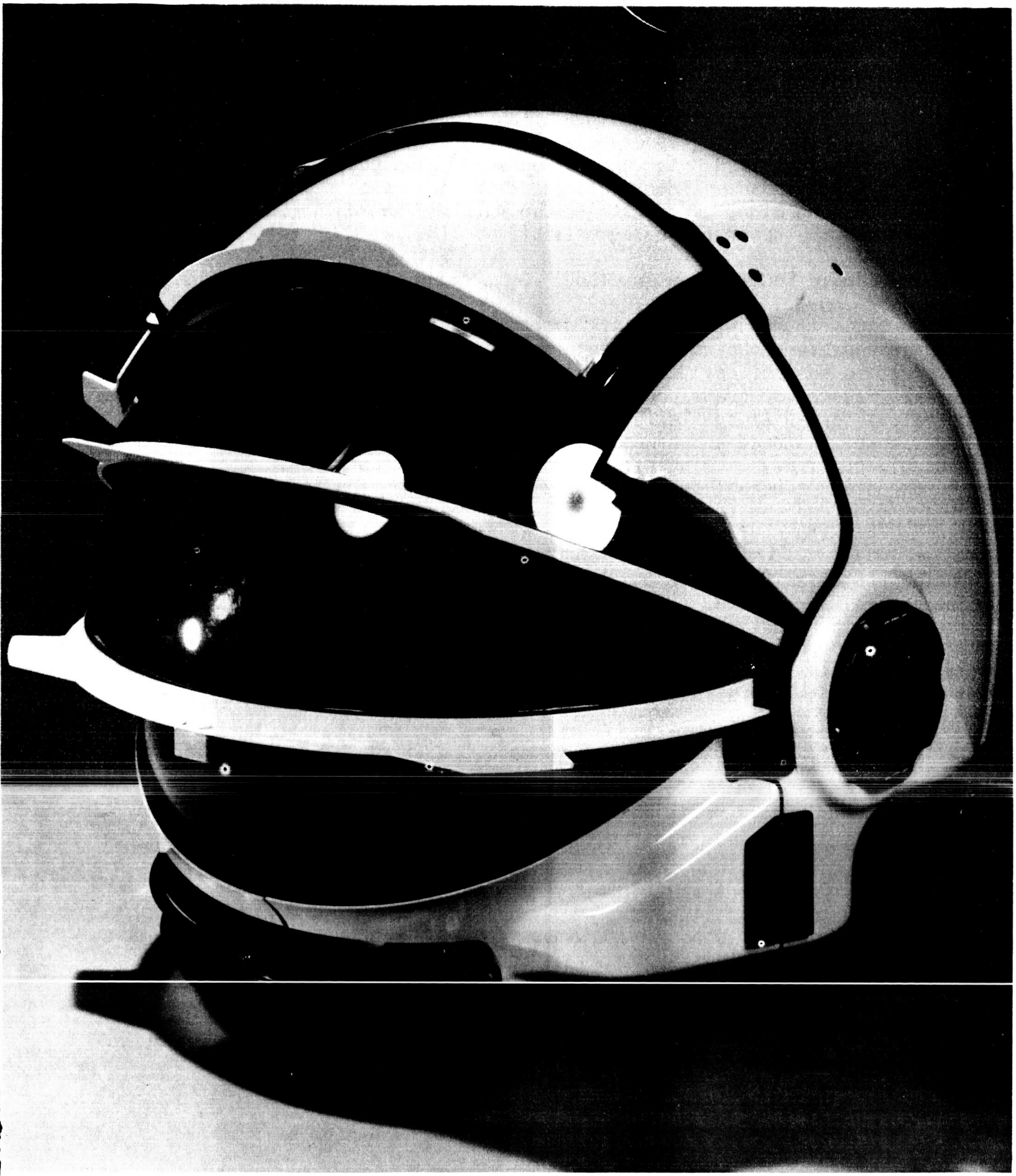


FIGURE 3-17: Helmet/Visor Assembly (SEVA)

3.2.5.4 Integrated Thermal Micrometeoroid Garment (ITMG)

In addition to providing thermal and micrometeoroid protection during EV operations, the ITMG is designed to protect the torso limb suit/assembly from abrasion, scuffing, and accidental puncture. The ITMG, in general, is a multilayer system using Super-Beta cloth, aluminized Kapton and Beta cloth marquiesette-aluminized Mylar and dacron scrim, and coated ripstop interliners, (Figure 3-18). In some ITMG's additional overcovers of teflon cloth are used whenever rubbing might occur between the multiple segments (such as between the EVVA and the upper torso segments of the ITMG).

3.2.5.5 Liquid Cooling Garment (LCG)

The LCG (Figure 3-19) consists of a "long handle" underwear type of garment which is capable of being worn next to the crewman's skin to provide comfort, perspiration absorbtion, thermal transfer to the ventilation system, and thermal transfer of crewman metabolic heat to the liquid cooling system. This moderately form-fitting flexible garment encompasses the entire body with the exception of the head and hands. The LCG is constructed of loose weave material to permit capillary wicking of body moisture for evaporation. It incorporates liquid coolant tubes of sufficient size and distribution to accomplish the primary body cooling requirements. The tubes are located in a pattern which assures intimate contact with the skin at all times.

The LCG distributes the cooling water to provide for primary body temperature control during EVA. The LCG body cooling capability, in conjunction with ventilation gas cooling, maintains the body thermal status within heat storage limits of +300 Btu and -300 Btu, respectively (for continuous metabolic rates averaging as low as 600 Btu/hr. or as high as 1600 Btu/hr. for 4 hours), when the cooling water supplied fulfills the following requirements:

• Inlet water temperature	37 to 53°F
• Water flow rate	o to 250 lb./hr.
• Supply pressure	Not to exceed 22.0 psia
• Pressure drop	1.0 to 5.0 psi

3.2.5.6 Communications and Telemetry

The communication and telemetry subsystems of the A-7L, A-7L-B, and the AES pressure suit systems are generally composed of the following hardware items (see Figure 3-20):

- Communication Carrier (headset)
- Electrical Harness
- Bioinstrumentation Harness
- Bioinstrumentation Belt

Typical A-7L-B ITMG Layup

T-162 Teflon Layer

4484A Super-Beta Layer

3 Layers Beta Marquisette

2 Layers 1/2 Mil Aluminized Kapton Film-Gridded (Kapton is crosshatched with 1/4" strips of Kapton tape to provide rip-stop capabilities)

5 Layers Perforated Aluminized (Aluminized both sides) Mylar

5 Layers Nonwoven Dacron

Neoprene Coated Rip-stop

Typical Orbital ITMG Layup

T-162 Teflon Layer

4484A Super Beta Layer

3 Layers Gridded/Krinkled *1/2 Mil Double Aluminized Kapton (Aluminized both sides)

2 Layers Sized Beta Marquisette (Kel F 800)

Neoprene Coated Nylon Rip-stop

* 1/2" strips of Kapton tape prestretched across Kapton in gridded pattern.

FIGURE 3-18: Comparison of A-7L-B Lunar and Orbital ITMG

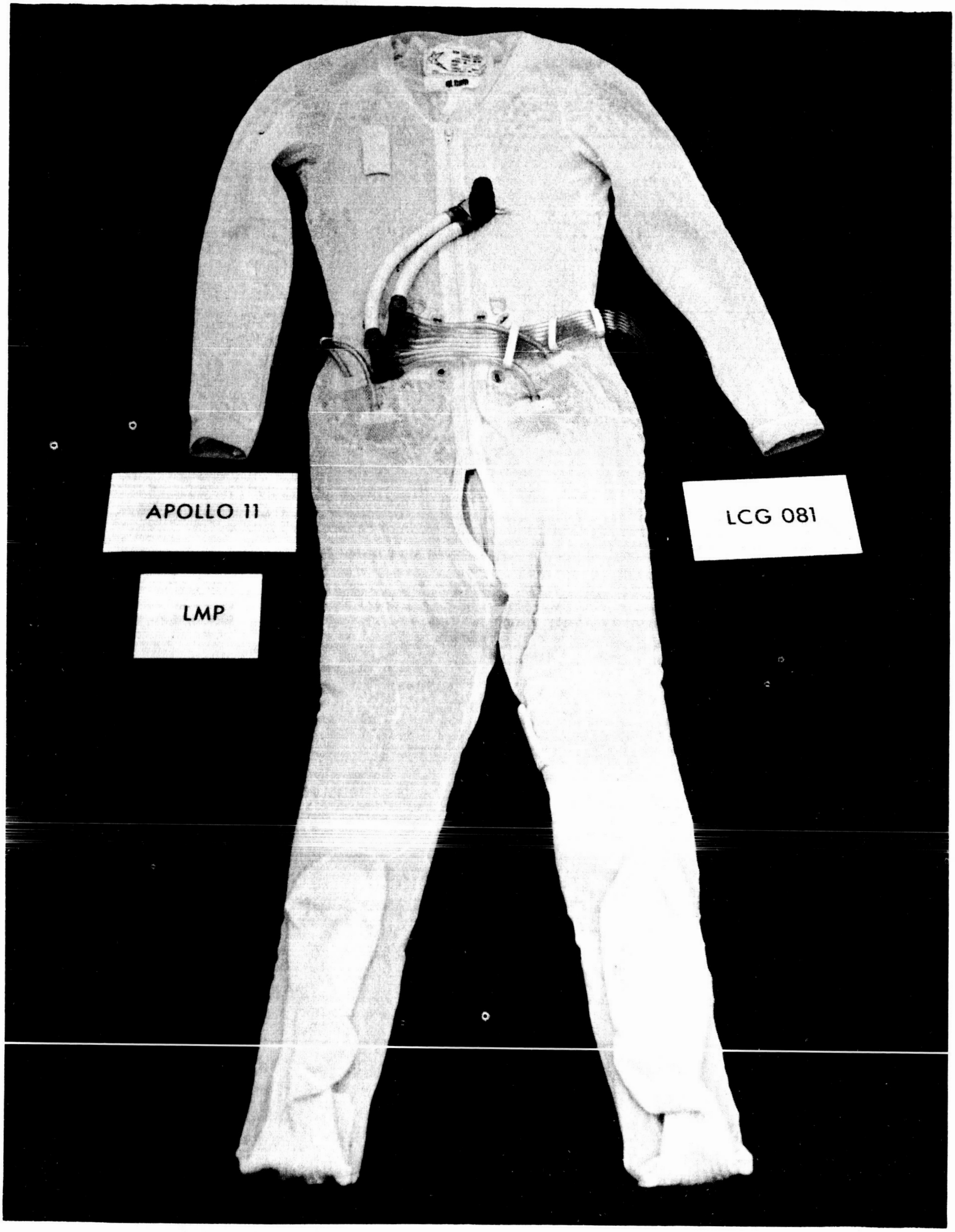


FIGURE 3-19: Liquid Cooling Garment (LCG)

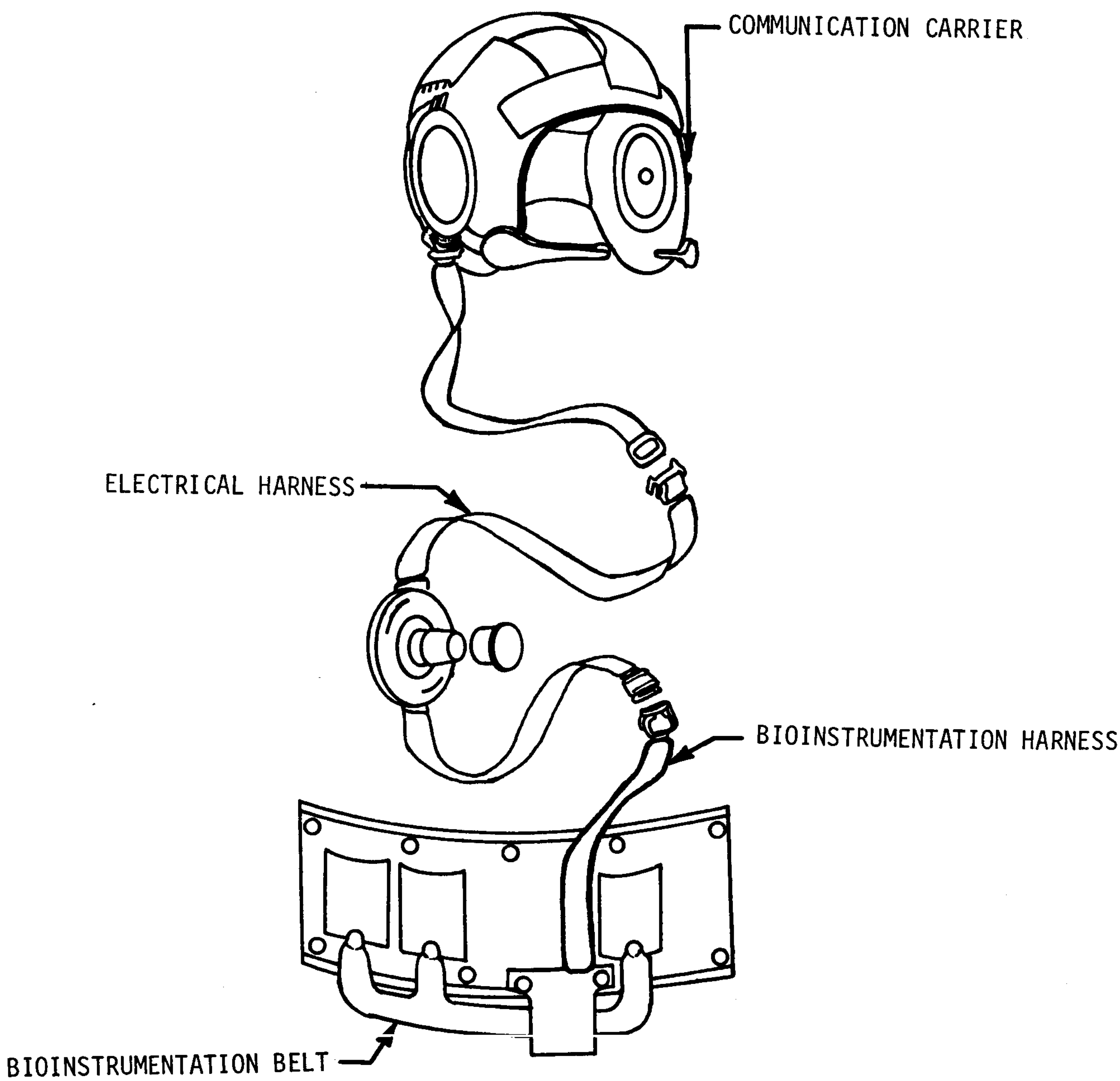


FIGURE 3-20: Sketch of Typical Communication/Telemetry Subsystem for Pressure Suits

In general, the vendors for the A-7L, A-7L-B, and AES pressure suit systems have been under contract to furnish the electrical and bioninstrumentation harnesses, whereas the communication carrier and the bioinstrumentation belt have been specified as Government Furnished Equipment (GFE). AiResearch has stated that the electrical and bioinstrumentation harnesses used in the development of their AES suit are identical to those used on the Apollo A-7L and A-7L-B suits. For the physical characteristics of the communication/telemetry subsystem components, see Tables 3-3 through 3-5. For the performance characteristics of this equipment, see Section 3.7.

3.2.6 Advanced Crew Protective System Design Considerations/Guidelines

During the Gemini, Apollo and Skylab Programs, a general set of crew protective system guidelines/considerations has evolved. This set, although broad in scope, will receive some degree of response during the development of advanced 8-10 psia pressure garment assembly. These guidelines/considerations are as follows:

- Minimum attention should be required by the suited crewman to assure that the system is performing properly.
- Materials selected for use in the pressure suit system should exhibit minimum ignition propagation, smoke, or toxic outgassing characteristics, even under the most hazardous of anticipated environments.
- Consideration must be made for providing adequate body cooling during pre- and post-EVA preparation periods.
- Adequate provisions for the stowage, protection, maintenance, and accessibility of the equipment and supplies must be assured.
- Pressure readout capability should be provided.
- Donning, doffing and servicing procedures should be included in an area adjacent to the activity.
- The system should be designed to minimize the effects of a nauseated crewman and the attendant effects.
- System design should be as simple as possible for the function it will perform.
- Emergency controls should be designed to be readily visible and accessible to the crewman.
- All controls/connectors which are utilized during checkout, donning, doffing, or operation should be easily accessible and visible.
- All control/connector operations should be single-handed and, preferably, controls/connectors should be designed so either hand may operate them.

- All controls/connectors should be operable while the astronaut is wearing EVA gloves and is in a pressurized mode.

- All connections affecting pressure integrity must have redundant locking devices which operate sequentially and may be visually verified.

- All connectors interfacing with life support systems must have the capability of providing an operationally acceptable method of vacuum transfer.

- All control positions should be verifiable without requiring recycling.

- All controls should be designed to prevent inadvertent actuation.

- Controls/connector actuations must be conducive to suit mobility.

- Pressure relief capability should be provided.

- Control/connector placement and accessibility should be determined by their criticality and utilization frequency.

- All connectors must be color coded; no two connectors should be the same color.

- Alignment marks should be provided on all keyed connectors.

3.3 AIRLOCKS AND SUPPORT EQUIPMENT

3.3.1 Introduction

During the Gemini and Apollo Programs, the only means of accomplishing the transition to/from an EVA configuration was to depressurize/repressurize the primary vehicle (Gemini Spacecraft, Apollo Command Module or Lunar Module). Due to the comparatively small vehicle volume, the number of EVAs required per flight, and the limited quantity of expendables lost per EVA, venting the primary vehicle was a feasible way of providing an EVA capability. However, with the initiation of the Skylab Program and the subsequent development of an orbital assembly that has a volume in excess of 10,000 cubic feet, it was readily evident that a vehicle hardware subsystem must be developed in order to accomplish the EVA transition. This subsystem is termed an airlock, and it permits astronaut (plus possible cargo) transition to/from an EVA configuration without a requirement to depressurize/repressurize the primary vehicle. See Table 3-9 for a summary of airlock technology.

3.3.2 Skylab Airlock Module (AM)

The Skylab Airlock Module (AM) is the only "flight-assigned" airlock that is currently being developed. It is scheduled to be launched with the Skylab Orbital Assembly in 1973 (ref. 3.22).

TABLE 3-9: Summary of Airlock Technology

PARAMETER	GEMINI PROGRAM	APOLLO PROGRAM		SKYLAB PROGRAM	SHUTTLE PROGRAM
		CM*	LM**		
● TOTAL VEHICLE VOLUME (ft^3)		250		10,000	
● MODULE VENTED	Vehicle	Vehicle	Vehicle	Airlock	Airlock
- Volume (ft^3)		250		153	Minimum 146
- Size (inches)		72x72x84		65 Dia.x 80	63 Dia.x 79
- Configuration	Cone	Cone	Rectangular	Cylinder	Cylinder
● DEPRESSURIZATION					
- Rate (ft^3/min)	"	"	"		
- Time (min)					
● REPRESSURIZATION					
- Rate (ft^3/min)	"	"	"		
- Time (min)					
● HATCH SIZES (Clearance)	22 x 40				
- EVA (inches)			28 x 30	22 x 40	30 Dia./30 x 50
- IVA (inches)				49.6 Dia.	30 Dia./30 x 50
● MAXIMUM NUMBER OF EVAs PER FLIGHT	2	1	4	6	6
● LIFE SUPPORT SYSTEM	Umbilical	Umbilical	PLSS	Umbilical	PLSS
● NUMBER OF CREWMEN					
- Per Flight	2	3	2	2	2
- Outside of Vehicle	1	1	2	2	2
- Pressure Suited per EVA	2	3	2	2	2
● CARGO VOLUME (ft^3)					
● RECHARGE STATIONS			O_2, H_2O	N_2 (Airlock Mod.)	

* C M - Command Module ** L M - Lunar Module

The AM structural assembly, as shown in Figure 3-21, consists of a Structural Transition Section (STS), a Tunnel Assembly, four (4) Airlock Truss Assemblies, a Flexible Tunnel Extension, a Fixed Airlock Shroud (FAS), a Deployment Assembly (DA), and a Payload Shroud (PS). The AM, Figure 3-22, connects the Multiple Docking Adapter (MDA) with the Orbital Workshop (OWS) in the Skylab cluster arrangement. For purposes of this subsection, primary attention will be given to the hardware components that directly support EVA or the Tunnel Assembly.

The AM Tunnel Assembly is a 65 inch diameter by 153 inch long cylinder that has a total volume of 300 cubic feet. It is divided into the following three compartments by two internal bulkheads equipped with hatches (see Figures 3-23 and 3-24):

- Forward Compartment
- Center (lock) Compartment
- Aft Compartment

3.3.2.1 Forward Compartment

The forward compartment connects the Tunnel Assembly with the STS and includes a cabin relief valve and provisions for support of stowage containers, tape recorders, and miscellaneous equipment.

3.3.2.2 Center Compartment

The center or lock compartment, 80 inches long with a volume of 153 cubic feet, is where EVA transition occurs. This compartment is equipped with a modified Gemini hatch (see Figure 3-25), an umbilical interface, and two EVA control panels (which control expendables to pressure suits). The AM is depressurized by venting to space and repressurized by venting to the OWS. At each end of the compartment is an IVA hatch (see Figure 3-26). These hatches are circular machinings 49.5 inches in diameter with radially attached stiffeners. An 8.5 inch diameter dual pane window in each hatch enables viewing of the lock from both forward and aft compartments. Each hatch is hinged to fold along the tunnel wall and to ensure correct closing orientation. The latching system utilizes a "run-around" cable system driving nine latch assemblies. A single stroke handle motion actuated through approximately 145 degrees operates the system. This required a 35 pound maximum load applied to the handle. An over-center detent device and positive lock are included in the handle system. The aft compartment hatch can be detached from its hinge by removing two quick release pins. It can then be reinstalled at the tunnel extension to isolate the AM from the OWS for "Contingency Mode" operations.

3.3.2.3 Aft Compartment

The aft compartment is 42 inches long and provides a recessed housing structure to support components of the atmospheric control system.

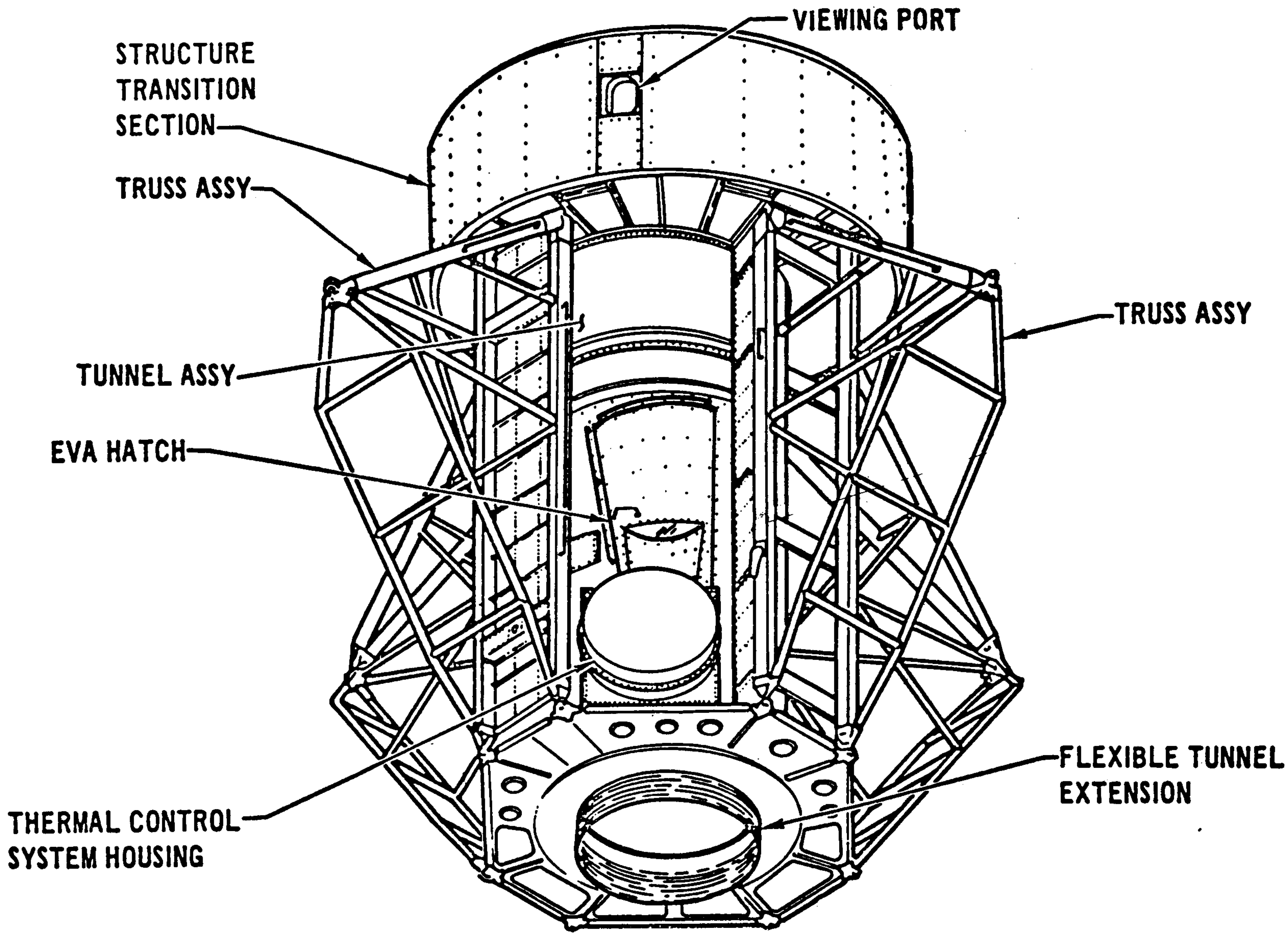


FIGURE 3-21: Airlock Module External Configuration

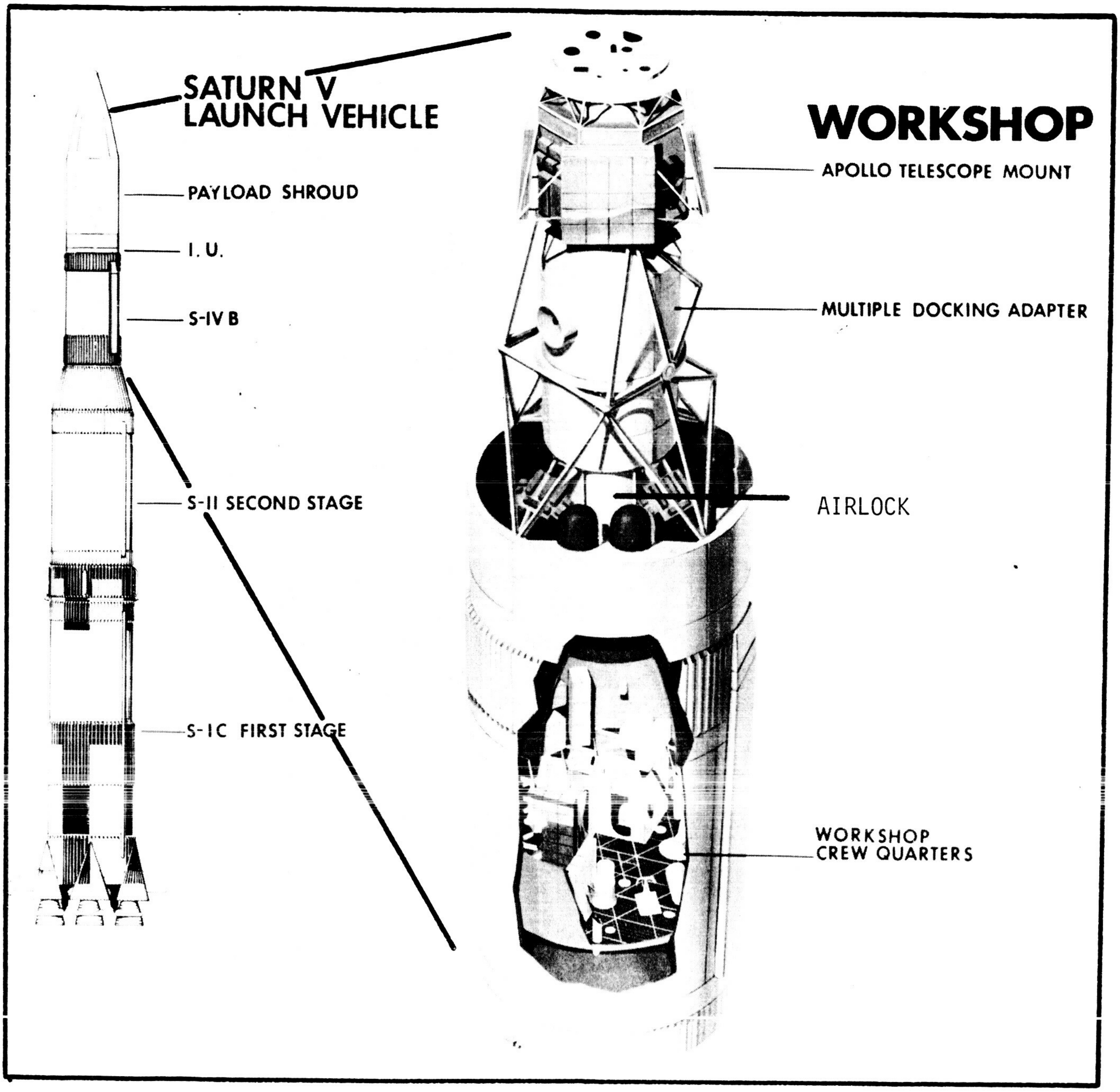


FIGURE 3-22: Airlock Module/Skylab Workshop Relationship

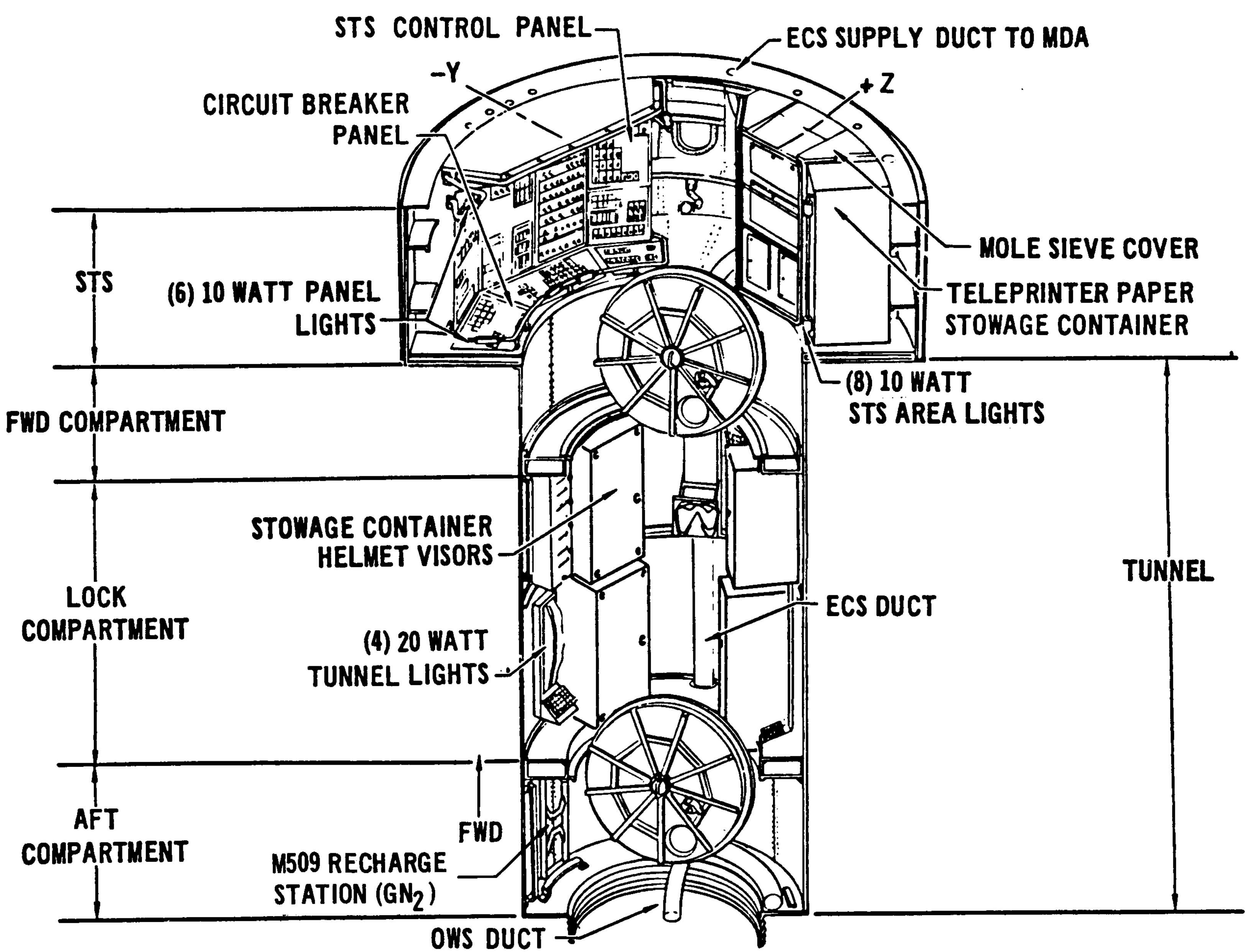


FIGURE 3-23: Airlock Module Internal Configuration - Control Panel Section (including STS)

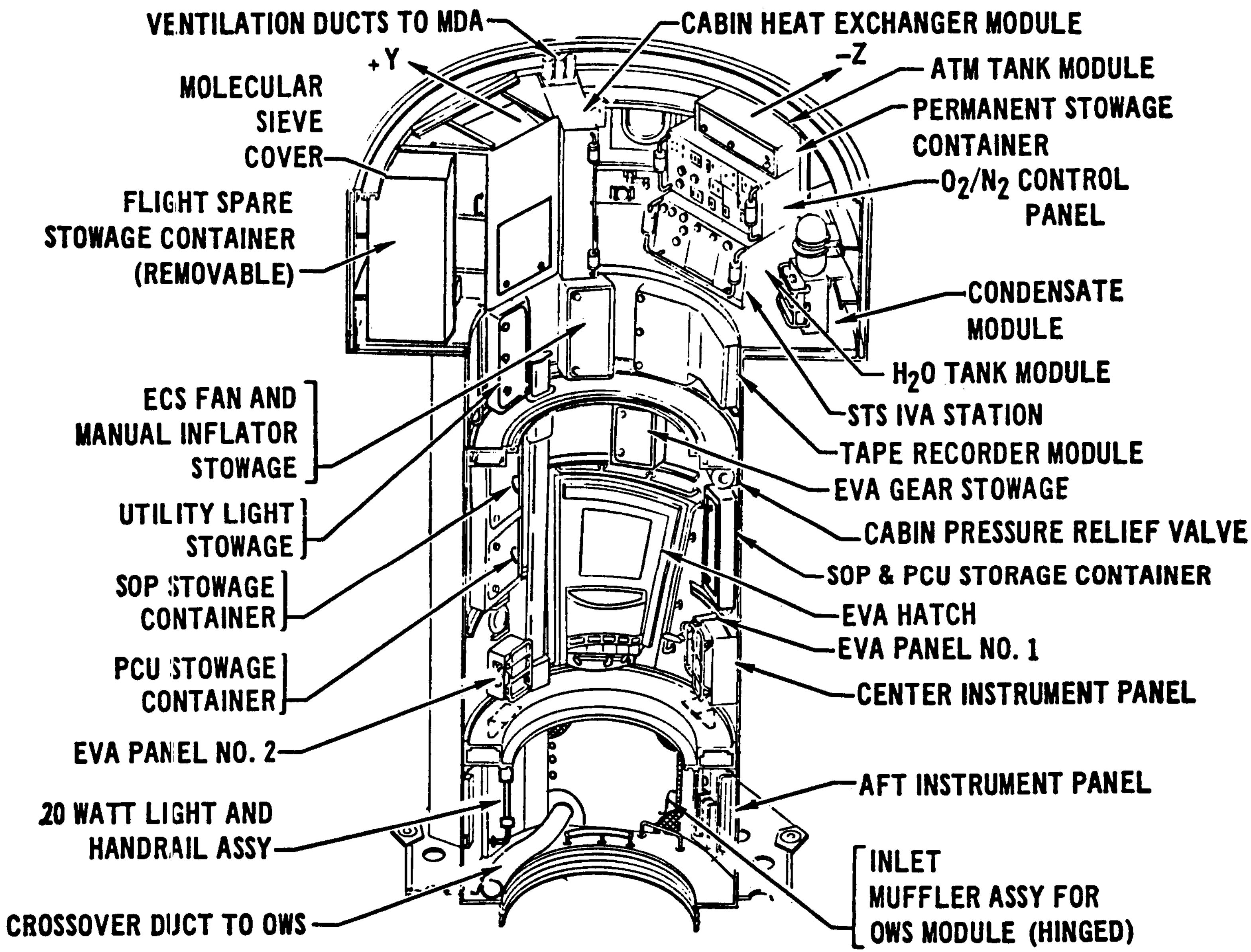


FIGURE 3-24: Airlock Module Internal Configuration - Hatch Section (including STS)

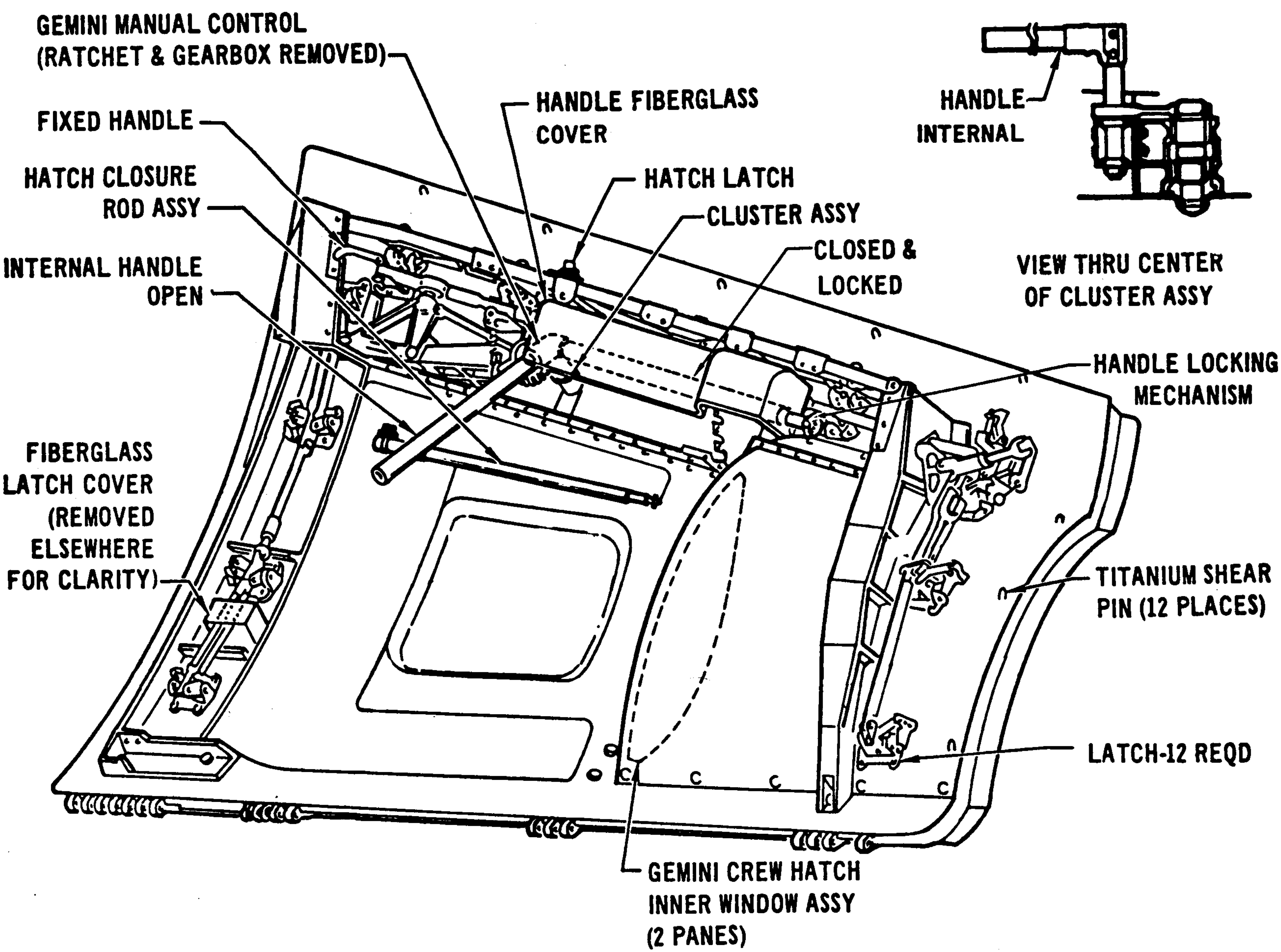


FIGURE 3-25: Airlock Module EVA Hatch

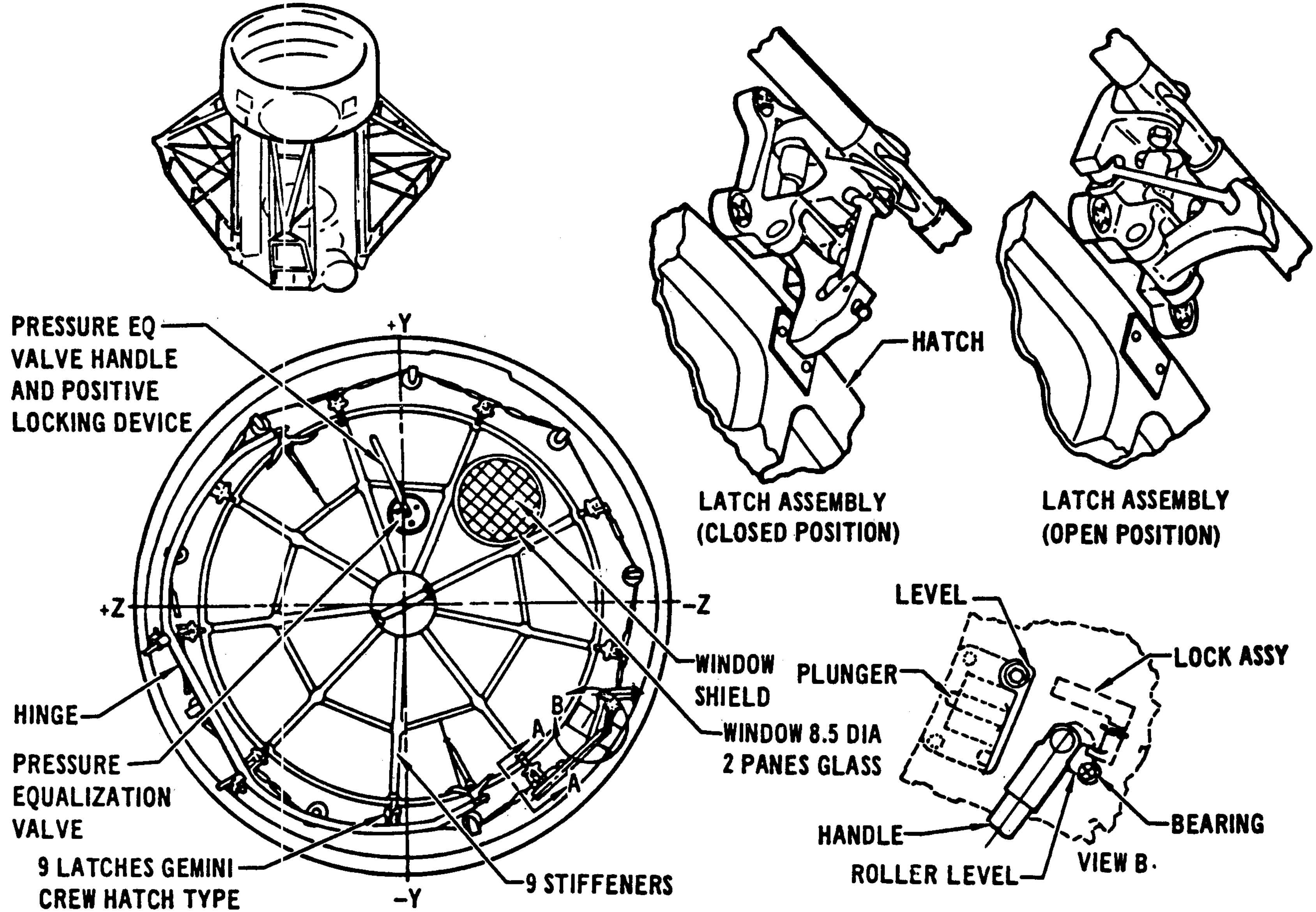


FIGURE 3-26: Airlock Module IVA Hatch

3.3.2.4 Crew Systems Support

Internal and external handholds, handrails, and a tether attachment system are provided for translation throughout the AM. The standard handhold or handrail provided is 1.40 inches wide by .62 inches thick and is mounted a minimum of 2.25 inches above the surface.

There are seven (7) 20 watt and eight (8) 10 watt frosted lens-type area floodlights located in the AM. Location of these lights is such that each section is illuminated enough to hold shadowing to a minimum without infringing upon crew comfort.

Internal voice communications in the AM are provided by an integral hardline system that is used in conjunction with the Apollo Voice Communications System. The aft compartment of the AM also contains a nitrogen (N_2) recharge station for supporting the Skylab M509 (Astronaut Maneuvering Unit) experiments.

See Table 3-9 for the physical, performance, and operational characteristics of the Skylab AM.

3.3.3 Shuttle Airlock

Although the Shuttle airlock is in an early stage of concept development, the following preliminary design requirements for Shuttle EVA/IVA orbiter support have been established (ref. 3.23):

- The maximum duration of airlock depressurization shall be eight (8) hours.
- The airlock will be designed to accommodate two crewmen wearing EVA equipment.
- Some EVA gear will be stowed in the airlock.
- Airlock repressurization will normally be accomplished by venting to the Shuttle cabin. Depressurization will take place by venting to space.
- Provisions for emergency rapid repressurization will also be provided.
- Airlock displays will include pressure and hatch closure verification.
- Proposed airlock dimensions are 63 inches in diameter by 79 inches long.
- Airlock control and displays will be located below the level of the PLSS.
- The required volume for airlock control is 6.0 cubic feet.
- The hatches into and out of the airlock must accommodate a 95th percentile crewman with EVA gear.

3.3.4 General Airlock Design Guidelines

Information presented below on airlock guidelines is drawn from a NASA airlock requirements document (ref. 3.24). A preliminary definition of the provisions required within and in support of general IVA/EVA airlock operations on future space stations is included. Provisions discussed include airlock location, size, hatches, controls, displays, communications, lighting, restraints, color coding, materials, environmental and thermal control and pressure suit interfaces.

3.3.4.1 Location

Airlocks on a space station should be located as near EVA worksites as possible to preclude long EVA translations and equipment transfers. Airlock location should also facilitate crew transfer between the space station and any docked vehicle.

3.3.4.2 Size

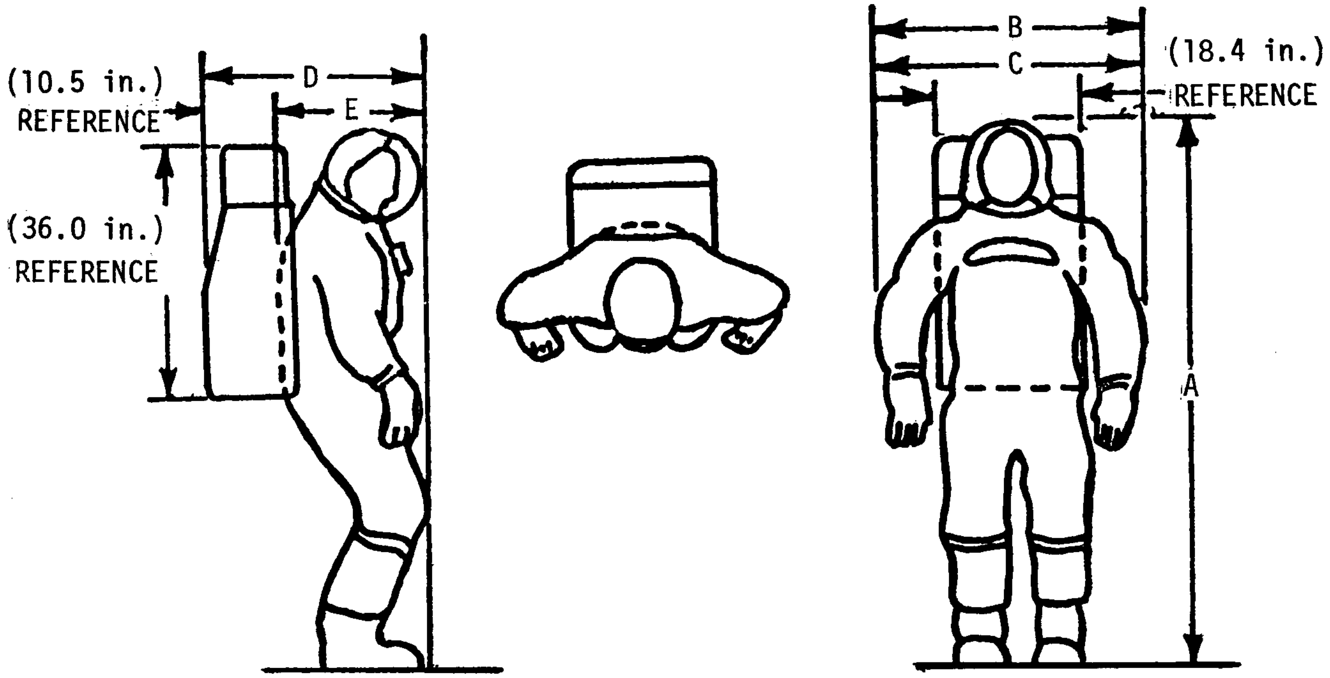
All EVA airlocks should be capable of containing at least one critical function maintenance package while occupied by two 95th percentile suited crewmen wearing their EVA support equipment. By international agreement for EVA/IVA airlocks, the usable floor area should be a minimum of 16.14 $ft.^2$ and the usable height a minimum of 6.652 ft.

While in an airlock, a pressure-suited crewman, should be capable of rotating a full 360 degrees in place, rotating end for end in the airlock, and, if occupying it with a companion, should be able to interchange positions easily with the other person. Handholds will be provided within the airlock if normal protuberances are not available. Figure 3-27 contains the envelope dimensions projected for 1981 of a suited/pressurized male crew member wearing a 3.7 psia pressure suit.

3.3.4.3 Hatches

Two or more hatches will be provided with each airlock. The intermediate or IVA hatch(es), located between the airlock and the space station cabin(s), and the EVA hatch(es), located between the airlock and "deep space", will be identical in operation and control. The hatch opening diameter should be a minimum of 3.28 ft. Hatch openings should be designed to minimize the effect on airlock volume and must accommodate a 95th percentile crewman with EVA gear. All EVA hatches must accommodate the required maintenance and experiment packages.

Hatches must be capable of being operated by one crewman without special tools. Handles for opening and closing hatches will be provided on both sides of the hatch cover. All hatches should be capable of being opened in sixty seconds and, further, should be capable of being closed to a safe "locked" position in sixty seconds. Hatches will swing open outward from the airlock. The direction of rotation of the hatch handle to open position should be clockwise, or up. The maximum load required to operate a hatch should be



Dimension	Percentile Man	
	5	95
A. Height	68.7 in.	76.8 in.
B. Maximum breadth at elbows (Arms Relaxed)	-	29.4 in.
C. Maximum breadth at elbows (Arms at Side)	-	26.4 in.
D. *Maximum depth with PLSS and OPS	26.0 in.	28.4 in.
E. *Maximum depth without PLSS and OPS	15.5 in.	17.9 in.
Weight, with PLSS/OPS	331.7 lbs.	404.6 lbs.
Weight, without PLSS/OPS	206.2 lbs.	278.9 lbs.

*To obtain envelope dimensions, 2 inches have been added to maximum chest depth of suited/pressurized crewman for PLSS control box.

NOTE: Measurements were made on A-7L PGA, pressurized to the 3.75 psig then projected for a 1981 man.

FIGURE 3-27: Male Crewman Anthropometric Dimensions in a 3.7 psig Pressurized Suit and PLSS

provided, and ΔP gauges should be provided on both sides of each hatch. During EV and IV pressurized suit activity, the hatch on the vacuum or lower pressure side of the airlock should remain open. Each airlock hatch should have a window.

3.3.4.4 Controls

As noted above, the airlock should be capable of being operated by one crewman without the need for special tools. All controls within the airlock will be safed or guarded to prevent inadvertent activation. Whenever the airlock is occupied by two crewmen, both crewmen will have simultaneous access to airlock controls.

3.3.4.5 Pressurization/Depressurization

Airlock pressurization will be possible from inside the space station and inside the airlock. This will normally be accomplished by venting from the space station cabin. The nominal rate for pressurizing the airlock from 0 to 14.7 psia should be between 0.0193 and 0.096 psi/sec. For emergency operation it should be possible to raise the airlock absolute pressure to slightly less (0.2 to 0.5 psi) than the pressure suit design operating pressure and to provide an atmosphere similar to the pressure suit design atmosphere within 15 seconds. The maximum rate that the airlock absolute pressure may be changed is 1.0 psi/sec. Overpressurization control must be provided.

Airlock depressurization will be possible from inside and outside the vehicles, as well as from the inside of the airlock. Airlock gas may be conserved through the utilization of pumpdown assemblies. Airlock pumpdown should be completed within 20 minutes. The normal depressurization rate should be between 0.0193 and 0.096 psi/sec. The airlock should be capable of being depressurized in 120 seconds, with the airlock gases and water vapor being vented to space. The depressurization valve to space vacuum should be located on or near the hatch and should utilize a torqueless nozzle. Airlock venting capability will need to be compatible with the purge rates expected from the pressure suit life support assemblies and maintenance/experiment packages as shown in Table 3-10. Vent ports should be located as remotely as possible from windows and experiment airlocks to minimize external contamination. Capability should be provided for conducting pressure suit pressure integrity checks for 3 to 5 minutes. Failure of a component in the vent system should not result in loss of airlock atmosphere.

3.3.4.6 Displays

Information necessary for airlock operation and control should be displayed both inside and outside the space station as well as inside the airlock. A tentative listing of the atmospheric information to be displayed, and where it should be displayed, is contained in Table 3-11. The operational displays provided in the airlock and within the space station will include:

- Hatch closure verification
- Communication system operation
- Depressurization of the airlock
- EVA in progress
- Opening of the airlock hatch

TABLE 3-10: Purge Rates for Pressure Suit Life Support Assemblies

Assembly	Purge Rate (Maximum)
Portable Life Support System (PLSS)	0.031 lb./hr.* at 3.75 psia
Oxygen Purge System (OPS)	8.4 lb./hr. at 4 psia
Life Support Umbilical (LSU)	13.7 lb./hr. at 6 psia
Secondary Oxygen Pack (SOP)	14.5 lb./hr. at 5 psia

*Leak rate for Pressure Garment Assembly (leak rate for PLSS is assumed negligible).

Caution and warning devices will be provided to signal the space station control center and the occupants of the airlock in the event of an airlock and/or space station emergency or loss of communication. Table 3-11 includes a tentative listing of the parameters requiring caution and warning.

3.3.4.7 Communication

Communications will be provided between the airlock and the space station control center. Communication connectors for the EVA communication system will be provided within the airlock. The airlock shall provide for both hardline and RF communication with an EVA crewman.

3.3.4.8 Lighting

The assemblies located within the airlock which the crewmen will use should be illuminated by light sources contained in the airlock. The general illumination in the airlock should be at least 1.9 foot-candles. The illumination for the assemblies and their displays/labels which the crewmen must monitor and operate should be at least 11.1 foot-candles. The crewmen may be provided with portable light for use in the airlock. The illumination of the

TABLE 3-11: Airlock Displays

Parameter	Location of Display			Caution and Warning Required	Display Information		
	In Airlock	In Station	Deep Space Side		Unit	Range	Tolerance
Airlock Total Pressure	X	X	X	X	mm Hg	0-1000	±10
Vehicle Total Pressure	X				mm Hg	0-1000	
Airlock O_2 Partial Pressure	X				mm Hg	0-300	
Vehicle O_2 Partial Pressure	X				mm Hg	0-300	
Airlock Temperature	X	X			°C	0-40	
Vehicle Temperature	X				°C	0-40	
PGA Pressure	X	X		X	mm Hg(a)	130-500	±5
Umbilical O_2 Supply Pressure	X	X			Atmos(g)	0-15	
Umbilical O_2 Supply Temperature	X	X			°C	0-27	±0.5
Umbilical Water Support Pressure	X	X			Atmos(g)	0-4	
Umbilical Water Supply Temperature	X	X			°C	0-27	±0.5
Umbilical Water Return Temperature	X	X			°C	0-27	±0.5
Umbilical Power	X	X			watt-hrs		
Vehicle O_2 Supply Quantity	X				Atmos.		
Vehicle Power	X				On		
Vehicle CO_2 Partial Pressure	X				mm Hg	0-30	
Ventilation Power	X				On		
EVA/IVA Elapsed Time		X		X	Hr:min:sec		

transfer routes outside the space station should be at least 0.9 foot-candles. It should be possible to turn the airlock lights on and off from inside and outside the space station and from inside the airlock.

3.3.4.9 Restraints

Appropriate mobility and restraint equipment should be incorporated for ingress, egress, and dwell time for zero-g operations. Provisions should be made in the airlock for stowage of equipment and for crewmen to be able to work in the airlock under zero-g conditions. Handholds must be provided on the space station exterior surface at all EVA hatches. If the airlock is part of a docking port, it should provide appropriate mobility and restraints equipment for cargo transfer. Tether attach points capable of withstanding a 440 lbs. static load are needed on the space station exterior surface at all EVA hatches for both crewmen and maintenance packages.

3.3.4.10 Color Coding

Color coding should be used as an operational aid; a tentative list of the airlock equipment to be color coded is contained in Table 3-12.

3.3.4.11 Materials

Primary pressure structural materials of the airlock should be nonflammable, with interior walls and secondary structures being self-extinguishing. Materials used in the airlock should not outgas toxic constituents in the lowest pressure environment to which they will be exposed.

3.3.4.12 Environmental and Thermal Control

When pressurized, the airlock atmosphere composition should be identical to the space station volumes. Revitalization of the airlock atmosphere shall be provided by the mixing of the space station atmosphere with the airlock atmosphere whenever an airlock intermediate hatch is open. Normally, the airlock hatches will be closed when the airlock is not in use. Atmospheric parameters to be monitored are described in Table 3-11. Minimum temperature of surfaces within the airlock whould be 55°F. Maximum temperature of these surfaces should be 105°F.

3.3.4.13 Pressure Suit Interfaces

The crew station within or near each airlock should have pressure suit life support system interfaces for the following:

- Recharging the Portable Life Support System (PLSS)
- Supporting the Umbilical Life Support System (ULSS)
- Supporting the Suit Umbilical Ventilation System (SUVS)

The recharge station interface for the PLSS will provide oxygen, water, and battery recharges. The umbilical station interface for the ULSS will

TABLE 3-12: Airlock Equipment Color Code

Equipment	Color
Airlock Depressurization Valve	Yellow
Pressure Equalization Valve	Yellow
Hatch Cover	White
Airlock Pressurization Valve	TBD
Oxygen Supply Valve (PLSS Recharge)	TBD
Water Supply Valve (PLSS Recharge)	TBD
Water Drain Valve (PLSS)	TBD
Drinking Water Supply Valve	TBD
Oxygen Supply Valve (Umbilical)	TBD
Umbilical Water Supply Connector	Blue
Umbilical Water Return Connector	Red
Ventilation Supply Connector	TBD
Ventilation Return Connector	TBD

provide oxygen, supply and return cooling water, and provide electrical power, voice communication, biomedical and other instrumentation readouts between the space station and the crewman. The umbilical station interface for the SUVS will provide cabin air for cooling the suited crewman prior to PLSS cooling activation. A minimum of two ULSS and SUVS stations will be provided within each airlock.

3.4 CREW AND CARGO TRANSFER SYSTEMS

3.4.1 Introduction

Movement of crewmembers and cargo has been successfully accomplished by several means during past mission EV activities. Crew transit over the exterior of the vehicle(s) in the orbital extravehicular environment was accomplished on

the Gemini and Apollo missions by the use of several types of fixed and portable handholds and handrails. Crew transfer between two undocked vehicles was demonstrated through free-floating techniques, self-propulsion and umbilical or tether pull-in. These methods were demonstrated within a maximum separation distance of 15 feet. Hand Held Maneuvering Units were evaluated briefly on the Gemini IV and X EVA missions as a free space personnel transportation device.

Orbital extravehicular cargo transfer on previous spaceflights has been limited to retrieval of small experiment samples on four Gemini missions and on Apollo 9. These transfer tasks were accomplished on the Apollo 9 flight by using vehicle mounted handholds and handrails and equipment and crew tethers (ref. 3.2).

Apollo 15 transearth crew and cargo transfer between the Command Module hatch and the Scientific Instrument Module (SIM) bay was accomplished using spacecraft mounted handholds and handrails. A wrist tether was used to restrain the cargo (film camera cassettes) during manual hand held transfer. The largest unit transferred, a 24 inch panoramic camera cassette, weighed 85 earth pounds.

The transfer of crewmen and large quantities of cargo over a wide range of distances on future manned space missions will require more advanced techniques and equipment than have been used on previous flights or those planned for use on scheduled future flights. The Skylab program, for example, will require the use of EVA to retrieve and replace film magazines from an experiment canister mounted within the Apollo Telescope Mount (ATM) structure. This extravehicular operation will require the EVA crewman to translate approximately 30 feet along the spacecraft structure to reach the task worksites. Standard handrails and handholds will be provided along the transfer routes for crewman translation. Electrically powered extendible booms will be used as the primary method of transferring cargo from the worksites to the Airlock Module (AM). As a backup mode to the extendible boom system, a manually actuated "endless clothesline" device will be available. Under nominal Skylab EVA operation, six excursions will be made to the external worksites and approximately 1500 earth pounds of cargo transported. This typical EVA task demonstrates the need for future EVA crew and cargo movement planned for future missions. The following sections examine man's available crew and cargo transfer systems and equipment capabilities for orbital EVA application.

3.4.2 Manual Extravehicular Crew Translation Devices

Most EVA crewman translation over the spacecraft surface will be achieved by using preinstalled or portable handholds and handrails. These translation aids are used where distances are relatively short and transfer time adequate.

EVA handholds normally consist of short sections of rectangular (the most useful shape) metal rail raised above the spacecraft surface 2.5 to 3 inches and attached to the surface at each end. The handrails may consist of a single unit or two parallel units mounted 18 to 22 inches apart and may vary in length depending on their application. They are mounted approximately

3 inches above the spacecraft surface. Table 3-13 presents the general characteristics of preinstalled EVA handrails and handholds used on Apollo and Skylab for EVA transfer operations (ref. 3.9).

3.4.3 Powered Crew and Cargo Transfer Systems - Astronaut Maneuvering Units (AMU)

A wide variety of crewman maneuvering equipment for free space application has been studied, designed, and, in some cases, tested in orbit during the Gemini program. In general, these devices provide the EVA crewman with a powered translational and rotational maneuvering capability. The use of free space maneuvering equipment permits point-to-point transit and cargo transfer in space when manual translation aids cannot fulfill EVA task objectives. The spectrum of crewman maneuvering equipment encompasses a wide range of units with respect to size and complexity. The range extends from the simple hand held propulsive device evaluated on the Gemini program to the Maneuvering Work Platform (MWP) being studied for future missions.

Maneuvering equipment can be classified into two categories: (1) automatically stabilized devices and (2) unstabilized or manually controlled units. The automatically stabilized devices are equipped with attitude-rate feedback sensors which provide automatic "hands-off" attitude stabilization (through the Reaction Control System). The manually controlled units rely on the crewman for rate sensing and for initiation of stabilization torques utilizing thrusters which are directionally aimed by the crewman.

The Astronaut Maneuvering Unit data presented in the following sections are concerned primarily with units to be flown on the Skylab program and with those being studied for future Shuttle and space station missions. These maneuvering units include the following:

- FCMU (Foot Controlled Maneuvering Unit)
- AMRV (Astronaut Maneuvering Research Vehicle)
  - ASMU (Automatically Stabilized Maneuvering Unit)
  - HHMU (Hand Held Maneuvering Unit)
- AMU (Astronaut Maneuvering Unit)
- MWP (Maneuverable Work Platform)

The maneuvering equipment to be evaluated aboard Skylab is contained in Experiments M509 and T020. Experiment M509 includes the AMRV, (ASMU and HHMU), and Experiment T020 evaluates the FCMU. The AMU and MWP are units being studied for future missions. A brief hardware description and the physical and performance characteristics of each of the units are included.

TABLE 3-13: EVA Handhold and Handrail Characteristics

SYSTEM	SYSTEM CHARACTERISTICS					
	GRIP CROSS SECTION	LOAD LIMITS (lbs.)	TYPE OF LOAD	DIRECTION OF LOAD	ALLOWABLE DEFLECTION (ins.)	REMARKS
HANDHOLDS	Rectangular 1.25 x .62 in. with .25 in. corner radius	600	Concentrated load	Any possible direction	0.5	• Standard Apollo type • Must provide 5.5 ins. of straight grasping surface
HANDRAILS	Rectangular 1.25 x .62 in. with .25 in. corner radius	600	Concentrated on most critical 2 ins. of member	Any possible direction	1.0	• Stand-off from spacecraft surface should be 2.5 ins. minimum for glove clearance

3.4.3.1 Hand Held Maneuvering Unit (HHMU)

Several HHMUs were developed, tested, qualified and carried on the Gemini flights for evaluation as astronaut extravehicular translating aids. The units were designed for use in the general vicinity of the spacecraft, and safety tethers were used as a distance limiting device and a backup method for returning to the spacecraft. Although only limited evaluation of the units was performed during the Gemini Program, due to spacecraft equipment problems, the feasibility of the HHMU was established. The HHMUs provided the necessary force to propel and/or stop the crewman by expelling a high pressure gas medium through pusher and tractor type thrusters. The unit is normally held in the right hand of the crewman and is pointed in the desired direction of flight while maintaining the force vector through his center of gravity.

The HHMUs are operated by squeezing a trigger mechanism that operates a throttle valve to provide gas flow to the tractor or pusher thrusters. The thruster is normally porportional to the displacement of the throttle valve trigger. A trigger preload force of 5 to 15 lbs. was common on the Gemini HHMUs. The characteristics of the Hand Held Manevuering Units designed for use on the Gemini flights are shown in Table 3-14. The Gemini IV and X units

TABLE 3-14: Gemini Hand Held Maneuvering Unit Characteristics

GEMINI HAND HELD MANEUVERING UNIT CHARACTERISTICS			
	Gemini IV	Gemini VIII	Gemini X
HHMU weight (lbs.)	7.5	3*	3*
Weight of propellant (lbs.)	.7	18	10.75
Propellant (gas)	Oxygen	Freon-14	Nitrogen
Thrust, tractor or pusher (lbs.)	0 to 2	0 to 2	0 to 2
Specific impulse calculated (sec.)	59	33.4	63
Total impulse (lb.-secs.)	40	600*	677*
Total available velocity increment (ft./sec.)	6	54	84
Trigger preload (lbs.)	15	15	5
Trigger force at maximum thrust (lbs.)	20	20	8
Storage tank pressure (psia)	4000	5000	5000
Regulated pressure (psia)	120	110±15	125±5
Nozzle area ratio	50:1	51:1	51:1

*The nitrogen propellant tank was mounted in the adapter section. The weight stated is for the HHMU only and does not include the weight of the umbilical, propellant tank and propellant.

were evaluated on-orbit. Another device, a hydrazine HHMU, has been developed and flight qualified for future missions. This unit was designed to improve the propulsion efficiency of the device by incorporating higher specific and higher density liquid monopropellant fuel. Analytic and experimental studies have been performed using 51% hydrazine and 49% water. The unit is currently in storage.

The Gemini HHMU's ground based simulation indicated that confused tumbling motions might occur due to inertia coupling effects, if excessive rotational velocities were reached. In view of this, rolling velocities were maintained close to zero and the crewman's mass distribution was kept as symmetrical as possible during the Gemini HHMU evaluations. Subsequent simulations have demonstrated that the inertia coupling effects are not as serious as believed during the Gemini simulations (ref. 3.2). The HHMU evaluation scheduled for the Skylab Program will include rotational maneuvers with some resulting part of the Astronaut Maneuvering Equipment experiment (M509) inside the Orbital Workshop (OWS) forward compartment.

The Skylab HHMU (see Figure 3-28) will be evaluated with the back-mounted Automatically Stabilized Maneuvering Unit (ASMU) in place. The HHMU incorporates one pusher and two tractor thrusters. Six degrees of freedom maneuverability is accomplished by orienting the thrust vector through the total center of gravity (CG) for translation and offset from the CG for rotation. The ASMU serves as a support module for HHMU evaluation. Propellant is supplied from the ASMU Propellant Supply Subsystem (PSS) through an umbilical. Instrumentation associated with the HHMU is mounted in the ASMU backpack unit. The Skylab HHMU characteristics are shown in Table 3-15 (ref. 3.9).

TABLE 3-15: Skylab Hand Held Maneuvering Unit Characteristics

SKYLAB HAND HELD MANEUVERING UNIT CHARACTERISTICS	
Weight of propellant (lbs.)	11.2/Tank
HHMU weight (lbs.)	3.0
Propellant (gas)	Nitrogen
Thrust, tractor or pusher (lbs.)	0 to 3.00±0.25
Specific impulse calculated (sec.)	58±2
Total impulse (lb.-sec.)	650/Tank
Total available velocity increment (ft./sec.)	53
Trigger preload (lbs.)	-
Trigger force at maximum thrust (lbs.)	-
Storage tank pressure (psia)	3000
Regulated pressure (psia)	145±10
Nozzle area ration (designed for 5 psia environment, tractor/pusher)	2.75/3.02

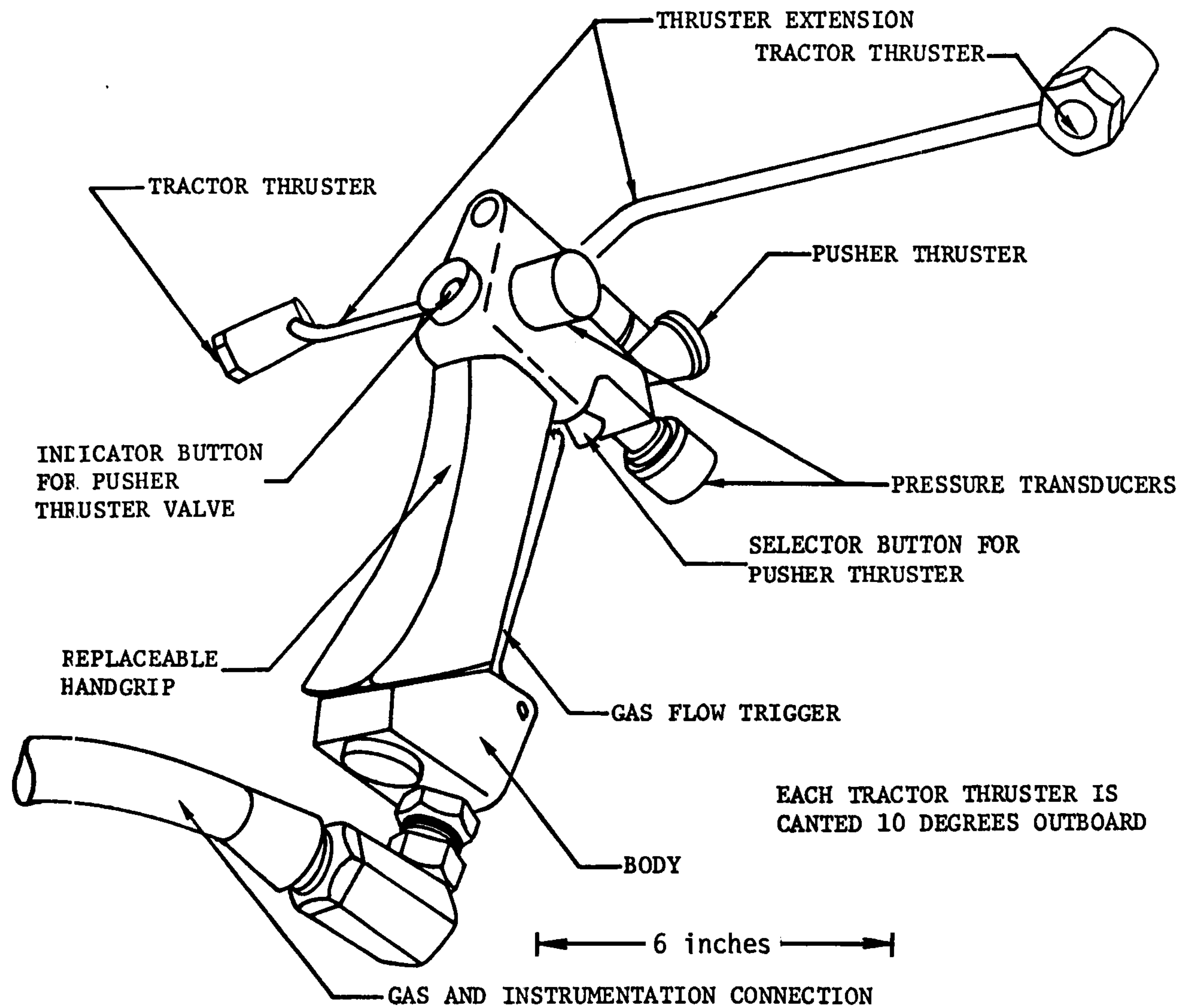


FIGURE 3-28: Hand Held Maneuvering Unit for Skylab Program

3.4.3.2 Astronaut Maneuvering Research Vehicle (AMRV)

The AMRV is an experimental test bed for the Astronaut Maneuvering Equipment (AME) experiments (M509) scheduled for evaluation during the Skylab Program. The AMRV is a combination of a back-mounted maneuvering unit with fixed position thrusters (the Automatically Stabilized Maneuvering Unit - ASMU), and a hand held unit with manually positioned thrusters (the HHMU). (The Skylab HHMU was discussed in Section 3.4.3.1.) The ASMU is normally flown with the HHMU attached, but the HHMU is not mandatory for ASMU operation. The HHMU requires support from the ASMU and cannot be flown independently.

The AMRV operates inside the pressurized Skylab orbital workshop and uses four control modes: HHMU, direct, rate gyroscope, and control moment gyroscope modes. These control modes are described below (ref. 3.9).

- HHMU Mode. The HHMU mode will evaluate man's maneuvering capability with a simple, lightweight, and completely manual hand held propulsion device to provide translational and rotational acceleration along and/or about the x, y, and z axes. The crewman is required to visually determine his attitude and attitude rates. When maneuvers are made, he must properly orient the HHMU (held in the right hand) and manually operate a throttle valve trigger for the desired thrust level and duration.

- Direct Mode. This mode will evaluate man's maneuvering capability with a backpack maneuvering unit without automatic attitude stabilization. It provides translational and rotational accelerations by means of rotational and translational hand controllers along and about the x, y, and z body axes. The hand controllers employ the same control logic as is used in the Apollo spacecraft. Constant angular acceleration is obtained through thruster firing when the rotational hand controller angle exceeds deadband threshold (± 0.5 degrees). Acceleration command is used for rotation and translation.

- Rate Gyro Mode. This mode employs the same thruster configuration and acceleration characteristics (acceleration command) as the direct mode but has automatic stabilization and attitude hold that is provided through rate gyro sensors and associated control electronics. Attitude rates are proportional to hand controller position up to 20 degrees per second. Upon return of the hand controller to the neutral position, rotational rates are reduced to less than ± 2 deg/sec with an attitude hold automatically maintained to within a deadband of ± 4.0 degrees. The control electronics incorporate pulse modulation to ensure maximum fuel economy in limit cycle operation. The rate gyro outputs are fed to the instrumentation subsystem during all modes of operation.

- Control Moment Gyro Mode (CMG). In this mode, attitude control is provided through momentum exchange instead of mass expulsion. The angular momentum of the CMGs is sufficient to passively resist small

external torques and to produce proportional attitude rates on command. Actuation of the rotational hand controller results in a torque applied to the appropriate gyro assembly to produce rotation about the desired axis. The rate of rotation (up to 5°/sec.) is proportional to the displacement of the controller. If the CMGs become saturated by external torques, the thrusters are automatically commanded by internal electronics to apply torque in the proper direction to desaturate the gyros. Acceleration command is again used for translation.

In addition to the HHMU and ASMU, the AMRV is supported by several principal components and subsystems included in the Skylab Astronaut Maneuvering Equipment package. The major sybsystems are listed below:

- Telemetry Receiver
- Telemetry Receiver Antennas
- ASMU Donning Station
- Batteries
- Battery Charger
- Propellant Supply Subsystem (PSS)
- PSS Stowage Rack
- Miscellaneous Hardware (back spacer, handgrips, etc.)

3.4.3.3 Automatically Stabilized Maneuvering Unit (ASMU)

The ASMU (Figure 3-29) is a back-mounted unit designed to evaluate the direct, the rate gyro, and the CMG control modes of the AMRV and to serve as a support module for the HHMU mode. It contains multiple fixed position thrusters located to produce translational forces through the total system center of mass and to produce pure rotational couples about each of the three body axes. The unit provides powered translational and rotational maneuvering capabilities in six degrees of freedom by means of fourteen thrusters centered about the overall system center of mass. The ASMU thruster orientation is shown in Figure 3-30. The major components of the ASMU are listed below. A brief description of each component or subsystem follows (ref. 3.9).

- Structures Subsystem
- Propellant Supply Subsystem
- Attitude Control Subsystem
- Electrical Subsystem
- Telemetry Subsystem
- Controls and Displays

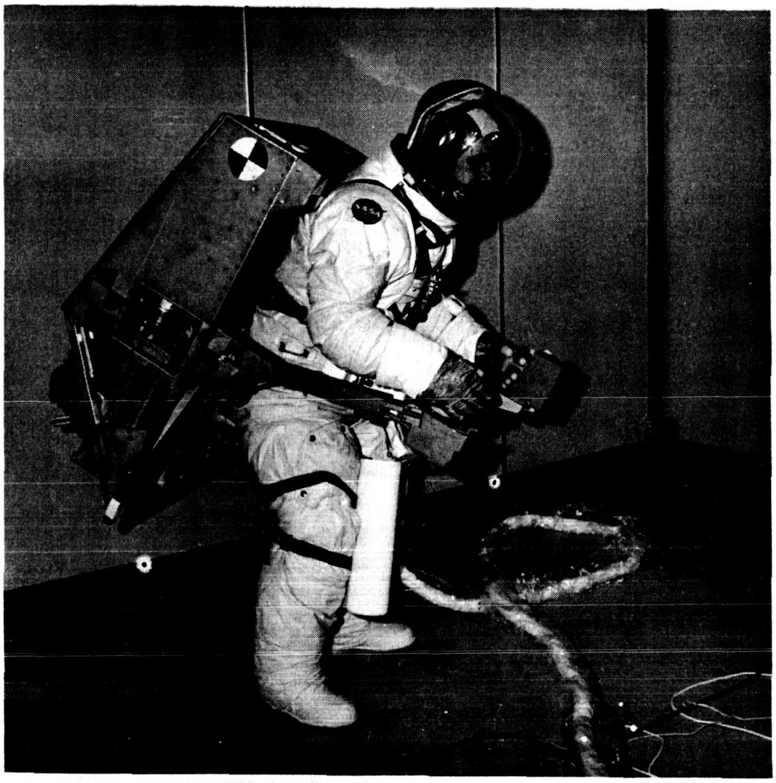


FIGURE 3-29: Automatically Stabilized Maneuvering Unit Shown with HHMU

Structures Subsystem

The basic structure of the ASMU is a truss frame of welded one-inch square aluminum tubes. It provides a rigid mount for the arms and seat assemblies, the PSS assembly, pneumatic control devices, and associated plumbing and various black boxes. The dimensional envelope is 41 x 27 x 13 inches and weighs approximately 23 pounds. Movable arms are attached to the frame to support both the hand controllers used for maneuver commands and the controls and displays required to be visible or accessible to the crewman. The arm length is adjustable and folds down for stowage and HHMU operation.

Propellant Supply Subsystem (PSS)

The propellant supply subsystem (Figure 3-31) provides high pressure nitrogen storage and pressure regulation capability as required for operation of the ASMU Propulsion Subsystem. It is supported in the ASMU by two quick release clamps, and it interfaces with the Propulsion Subsystem through a flexible hose connection. Three units are provided for inflight operations. They are stowed in the PSS Stowage Rack for launch and during those times when they are not being used for an experiment. The PSS units will be recharged in the Airlock Module during flight. Two operations will be required

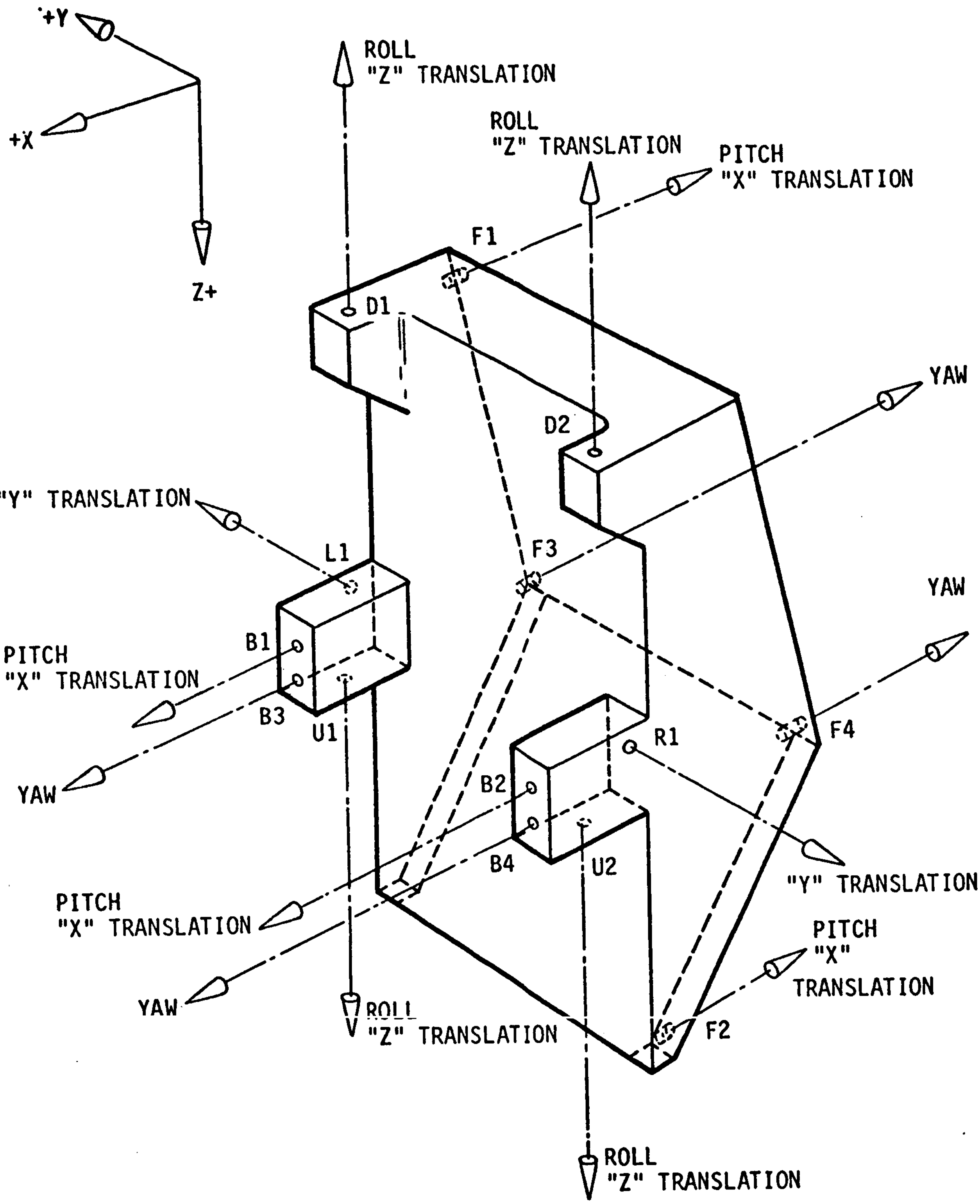


FIGURE 3-30: ASMU Thruster Orientation

for a full charge -- an initial charge and a topping-off charge. Each operation will take approximately 3 to 5 minutes with appropriate time allowed for the pressure vessel to cool down. The complete PSS assembly weighs approximately 57.4 pounds (including full gas charge).

The PSS subsystem consists of:

- A pressure vessel and cover
- A temperature probe
- A pressure regulator assembly

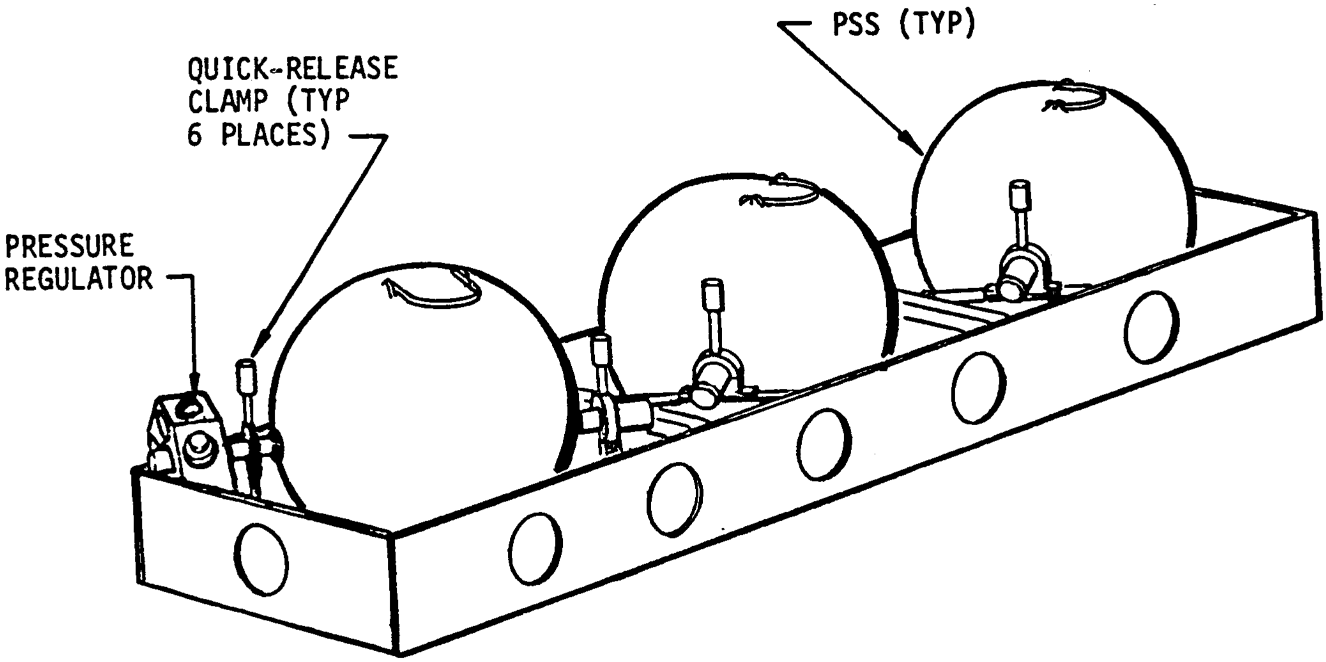


FIGURE 3-31: Propellant Supply Subsystem for ASMU and HHMU

The pressure vessel is a 1500 cubic inch, 14.5 inch diameter sphere that operates from 3000 psig down to 250 psig. It is provided with a cover consisting of aluminum half spheres for protection during maneuvering handling. Two bosses are provided on the pressure vessel to carry the load to the ASMU. The temperature probe is attached to one boss and the regulator to the other. The cover assembly is provided with a handle for ease in transporting the complete PSS assembly. The pressure regulator assembly consists of a relief valve, a supply valve, filters, a pressure transducer, a pressure gauge, a regulator, and quick disconnects.

Attitude Control Subsystem (ACS)

The Attitude Control Subsystem consists of the equipment necessary to convert the pilot's manual commands to electrical signals, process these signals, route them through various stages of control logic, and apply them as stimuli to the motion-producing devices. The units comprising the subsystem include the following:

- Translational Hand Controller (THC)
- Rotational Hand Controller (RHC)
- Rate Gyro Assembly (RGA)
- Control Moment Gyro Assembly (CMGA)
- Control Electronics Assembly (CEA)

The ACS interfaces with the Electrical Subsystem for power with the Controls and Displays Subsystem (C&DS) during mode and power commands, with the Propulsion Subsystem for thruster actuation, and with the Instrumentation Subsystem for system monitoring.

Electrical Subsystem

The ASMU Electrical Subsystem consists of the equipment necessary to provide and distribute electrical power throughout the ASMU. The subsystem consists of a flight battery, a junction box, and associated wiring.

The battery is nickel cadmium and is rated at 6 ampere-hours. It contains a zero-g power connector, a test connector for troubleshooting, and a 30 ampere push-pull circuit breaker. The electrical subsystem interfaces with the Battery Charger for external power and battery recharging. The Instrumentation Subsystem monitors and the Electrical Subsystem buses voltage and current drain. Each monitored parameter is a 0-5 VDC analog signal.

Instrumentation Subsystem

The Instrumentation Subsystem consists of the transducers and signal conditioners required to gather and condition the desired system data for presentation to the Telemetry Transmitter. The subsystem interfaces with all other subsystems for the various instrumented parameters. Many of these are conditioned by their source unit such that the Instrumentation Subsystem needs to provide only cabling to the Telemetry Transmitter. Power to the subsystem (+28 VDC) is provided by the Electrical Subsystem. The subsystem presents thirty 0-5 VDC analog signals and twenty-five bilevel signals to the data transmitter for conversion, format, and transmission. The data encoder in the telemetry transmitter generates a basic bit rate of 5760 bits per second.

Telemetry Subsystem

The Telemetry Subsystem includes the equipment necessary to process the instrumented data and transfer them to the OWS Data Storage Equipment (DSE).

The subsystem hardware includes a Frequency Shift Keyed (FSK) transmitter, an FSK receiver, and associated transmitting and receiving antennas. The system operates at 261.075 MHz.

The subsystem interfaces with the Electrical Subsystem for power to the transmitter and the battery charger for power to the receiver. The Instrumentation Subsystem, TM receiver switches, and the AM timing word generator provide the subsystem with data inputs. General characteristics of the ASMU are shown in Table 3-16:

TABLE 3-16: Skylab Automatically Stabilized Maneuvering Unit Characteristics

SKYLAB AUTOMATICALLY STABILIZED MANEUVERING UNIT CHARACTERISTICS	
Weight (lbs.)	256.5
Volume (ft.^{3})	20
Dimensions (in.)	27x41.5x48 (Deployed)
Propellant, gas	Nitrogen
Propellant weight (lbs.)	11.2/Tank
Stowage tank pressure (psia)	3000
Regulated pressure (psia)	145 $\pm$10
Propellant supply subsystem weight (lbs.) .	57.4 (charged)
Propellant flow rate to thrusters (lbs./sec.)	0 to 0.095
Operational time per tank (min.)	30 (approx.)
Quick disconnect force requirements (lbs.) .	25 (max.)
Power, battery	+28 vdc, 6 ampere-hours

Controls and Displays

The Controls and Displays subsystem consists of separate rotational and translational hand controllers, a mode selection switch, a propellant isolation switch, and a self-contained propellant pressure gauge. Flight with the ASMU is expected to be similar to maneuvering the Apollo spacecraft. Hand controllers will be similar to those of the Apollo spacecraft with the left-hand controller used for translation control, and the right-hand controller used for rotational control.

3.4.3.4 Foot Controlled Maneuvering Unit (FCMU)

The Foot Controlled Maneuvering Unit experiment (T020), to be conducted within the Skylab orbital workshop, will evaluate the use of a relatively simple astronaut maneuvering device for future crew and cargo transfer applications. The maneuvering device (Figure 3-32) offers a combination of simplicity, reliability and performance capabilities not provided in the usual

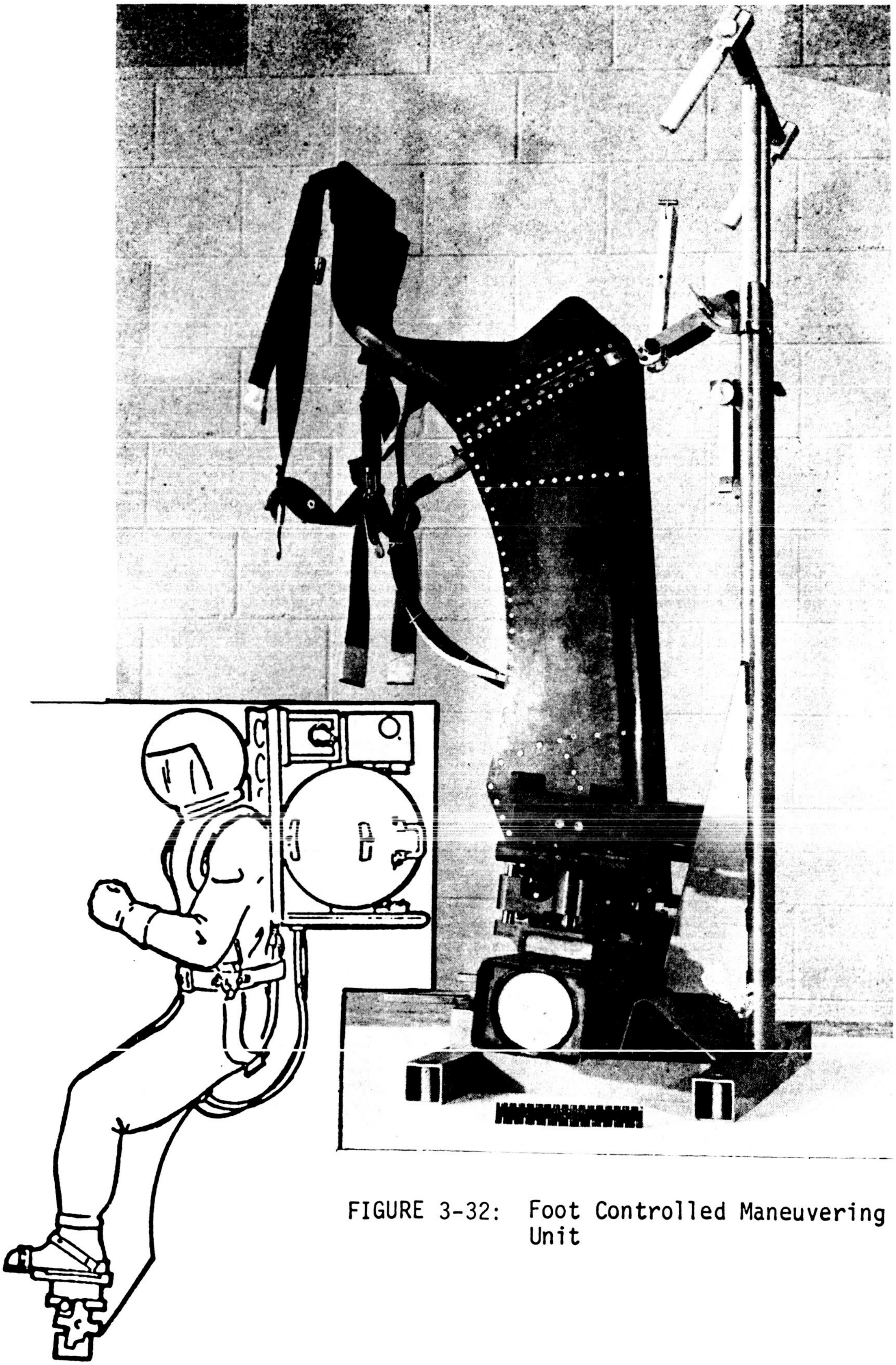


FIGURE 3-32: Foot Controlled Maneuvering Unit

maneuvering unit design approach. The foot controlled system will allow the crewman to control his attitude about three axes and to translate along the vertical body axis. The unit will provide "hands-free" operation for task performance and cargo transfer (ref. 3.9)

The FCMU employs foot operated controls, unbalanced-attitude thrusters and translational thrusters acting along the near vertical body principle axis. The unit is straddled by the crewman while performing the maneuvering activities. The flight hardware consists of the FCMU device, the Shoe Plate Assemblies, a Mounting Fixture, a Propulsion Gas Supply Unit (PGSV) Assembly, and a Waist Belt. A brief description of the equipment follows:

- FCMU - Consists of a framework with a saddle seat and restraining straps to secure the crewman to the unit. A bracket is provided to mount a Data Acquisition Camera (DAC) with a split image mirror. Two, four-nozzle thruster assemblies (foot controlled) are attached to the framework to provide attitude and translational accelerations. It is operated in either the suited or unsuited mode.

- Shoe Plates - The shoe plates fasten to the shoes of either the Shirtsleeve Garment Assembly (SGA) or the Skylab Extravehicular Mobility Unit (EMU) and allow the crewman to step into and be securely fastened to the FCMU foot pedal assemblies.

- Mounting Fixture - Used to stow the FCMU and the Backpack (PGSU) during launch and after experiment runs. Also provides aids and restraints for crew mounting and dismounting.

- PGSU Assembly - Supplies cold gas propellant (N_2) to the thrusters and electrical power to the DAC. A battery and Propellant Supply Subsystem (PSS) from Experiment M509 are used.

Characteristics of the FCMU are shown in Table 3-17.

3.4.3.5 Astronaut Maneuvering Unit Brassboard (AMUB)

The Astronaut Maneuvering Unit Brassboard (AMUB) project was undertaken to demonstrate the feasibility of a simple six-degrees-of-freedom cold gas maneuvering unit. The Brassboard is a laboratory model designed for an unsuited, shirtsleeve operator. The device is functionally equivalent to a flight article maneuvering unit. The AMUB employs 16 one-pound, nitrogen thrusters mounted on a collapsible aluminum alloy frame (see Figure 3-33). Regulated nitrogen gas is supplied to the thrusters from an external source. Translational commands are applied by thrusters located in a plane passing through the operator's center of mass. Attitude commands are applied as pure couples using the appropriate thrusters.

The AMUB was initially designed as an acceleration command system, i.e., the translational or attitude thrusters would remain "on" as long as the command persisted. However, an attitude stability augmentation system was designed which converts the acceleration commands into rate commands.

TABLE 3-17: Foot Controlled Maneuvering Unit Characteristics

FOOT CONTROLLED MANEUVERING UNIT CHARACTERISTICS	
Weight (lbs.)	59.1**
Stowage Volume (ft.^{3})	23 (approx.)
Stowage dimensions (ins.)	25.5 x 28 x 54
Propellant, gas*	Nitrogen
Propellant weight (lbs.)*	11.2/Tank
Stowage tank pressure (psia)*	3000
Regulated pressure (psia)*	145 $\pm$10
Propellant supply subsystem weight (lbs.)* .	57.4 (charged)
Propellant flow rate to thruster (lbs./sec.)*	0 to 0.095
Thrust (lbs.)	0.3 to 1.0
Power, battery*	+28 vdc, 6 ampere-hours
Translational acceleration (ft./sec.^{2}). . . .	0.1
Attitude acceleration (°/sec.^{2})	4

*The PSS and battery are also used on Skylab experiment M509.

**Does not include weights of propellant supply subsystems or battery.

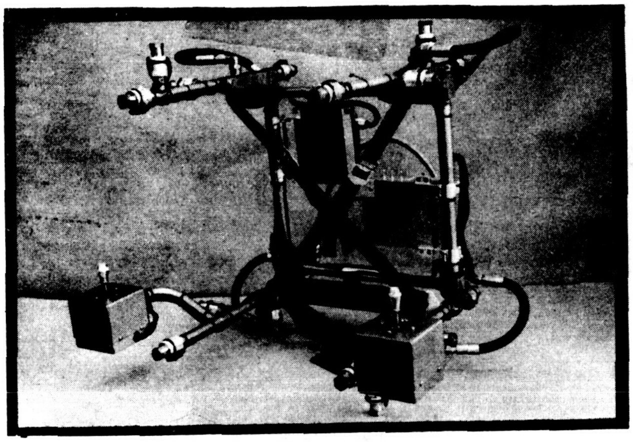
Commands originate at two hand controllers (see Figure 3-28) which can be displaced in the direction of the desired motion. The left-hand controller commands translation; the right-hand controller commands attitude. AMUB characteristics are summarized in Table 3-18 (ref. 3.25).

The AMUB was tested on an air bearing surface to evaluate its characteristics in a three-degrees-of-freedom environment. The fidelity of the test equipment, however, did not allow a conclusive evaluation to be performed.

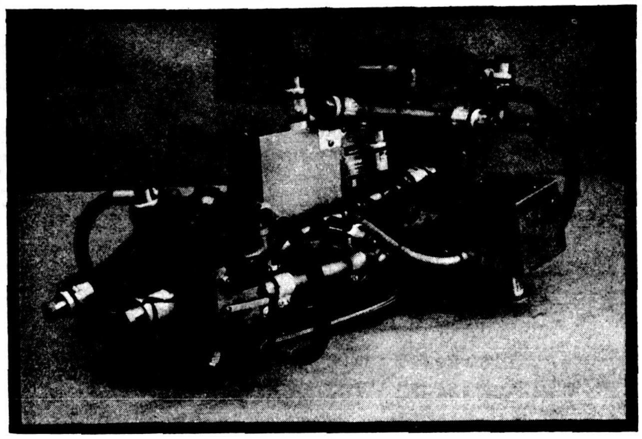
3.4.3.6 Integrated Maneuvering Life Support System (IMLSS)

The Integrated Maneuvering Life Support System (IMLSS) was designed to investigate the feasibility of incorporating a cold-gas maneuvering system into an existing, integrated suit/life support system design. As designed, the system would afford totally independent extravehicular operation. The IMLSS provides environmental protection, life support, and maneuvering, which, combined with unaided expendables recharge, results in the capability of extravehicular mission durations limited only by the crewman's endurance rather than by hardware design.

The maneuvering system of the IMLSS is based on direct firing of multiple fixed-position thrusters to provide translational and complete rotational capability (see Figure 3-34). Hand controllers located on the sides of the



A. Deployed



B. Folded

FIGURE 3-33: Astronaut Maneuvering Unit Brassboard (AMUB)

maneuvering unit allow command inputs to be made. Eight electrical solenoid thrusters (gaseous oxygen) are arranged as shown in Figure 3-34. The thruster firing characteristic is either full on or full off. Tubing for the cold gas propellant from the propellant tank module to the thrusters is flush with the suit surface but is exterior to the pressure garment. The thrusters are configured to produce pure couples for rotation and to minimize cross coupling. The thrusters fired for translation do not impart rotations. Accelerations about each control axis are shown below (ref. 3.15):

Angular:	
Pitch, Roll, Yaw	$10°/sec^2$ to $50°/sec^2$
Linear:	
Fore and Aft	0.4 ± 0.1 ft/sec^2
Vertical and Side	0.25 ± 0.05 ft/sec^2

3.4.3.7 Astronaut Maneuvering Unit (AMU)

Presently, there are two candidate post-Skylab experiments with emphasis on the development of advanced extravehicular mobility systems. These systems are the Astronaut Maneuvering Unit (AMU) and the Maneuvering Work Platform

TABLE 3-18: AMU Characteristics

Overall Size -	
Deployed	18 x 18 x 22 inches
Folded	13 x 32 x 8 inches
Gross Weight	
Without Stability Augmentation	16 lbs.
With Stability Augmentation	25.5 lbs.
Functional Characteristics	
Each thruster develops 1 lb. thrust with 180 psig feed pressure	
Thrust level (adjustable by lowering feed pressure)	
Fore-Aft	2 lbs.
Lateral	1 lb.
Up/down	2 lbs.
Attitude commands produce pure couples	
Attitude commands inhibit translational commands	
Stability Augmentation System	
Adjustable Rate Command ±5 deg/sec to ±15 deg/sec	
Adjustable Rate Deadband 0 to ±5 deg/sec	
Adjustable Rate Command Hysteresis - 0 to 2 deg/sec	

(MWP). The objectives of these experiments are to: (1) assess and develop man's ability to efficiently use the maneuvering systems in performing extravehicular activities; (2) develop the operational skills required for navigation, docking/anchoring, cargo transfer, resupply, astronaut rescue, space assembly, maintenance and repair, and (3) develop the hardware and procedures required to support future extravehicular manipulations (ref. 3.26).

The AMU (Figure 3-35) is a back-mounted system with multiple fixed-position thrusters. Six Control Moment Gyros (CMG), arranged in pairs along the three body axes, provide automatic stabilization and attitude control. A cold-gas reaction control system is used to provide thrust for translation and to produce restoring torques for CMG momentum dumping. The AMU has electrical power data communication, gas supply, and life support subsystems to allow operation of the unit independent of umbilicals to the spacecraft. A hand controller is used to provide control signals to torque the gyros for changing attitude. A separate hand controller is used to activate the thrusters for translational control.

Interchangeable high-pressure gas bottles are used for supplying the oxygen for the crewman life support system (LSS) and propulsion gas. Available AMU system characteristics and performance requirements are listed in Table 3-19.

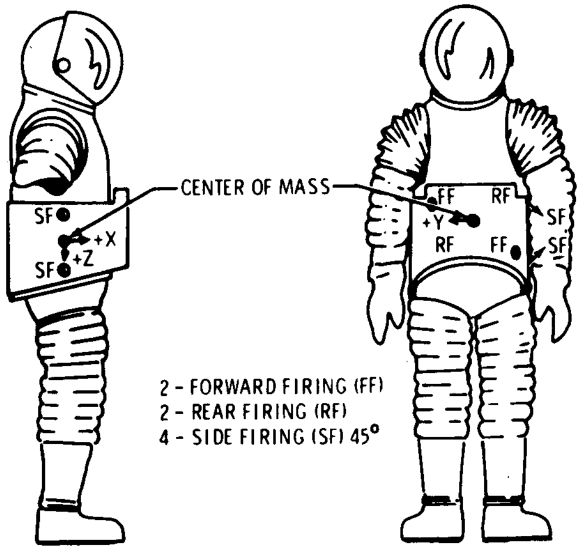


Figure 3-34: Integrated Maneuvering Life Support System (IMLSS) Thruster Configuration

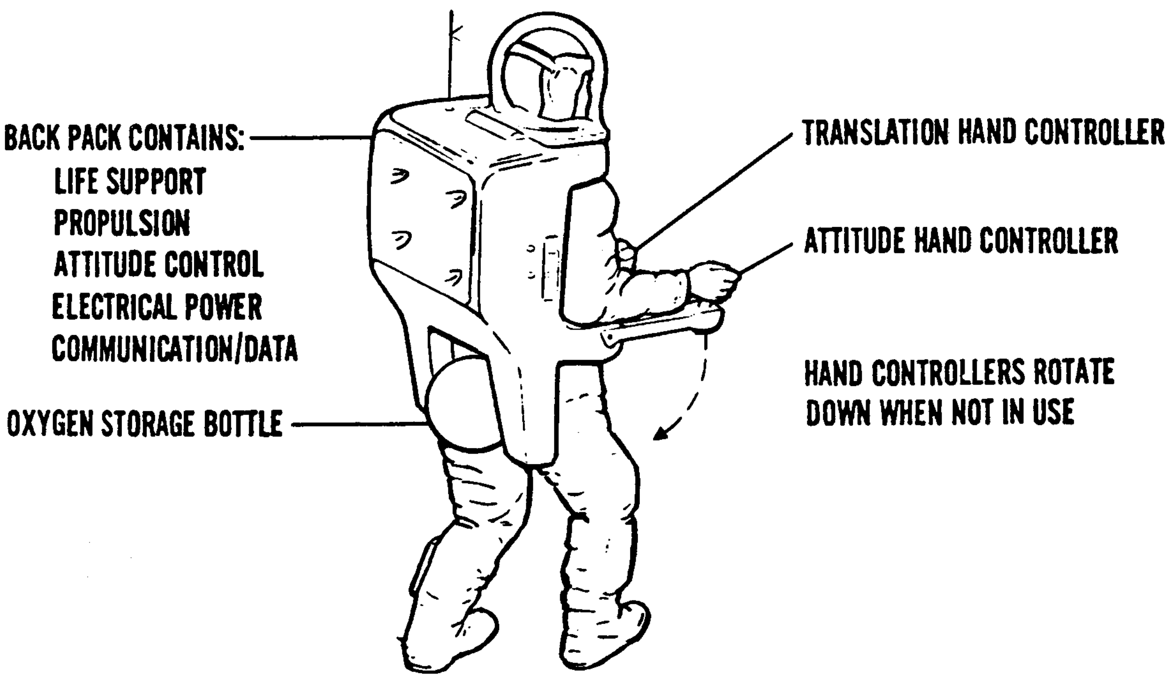


FIGURE 3-35: Astronaut Maneuvering Unit

TABLE 3-19: AMU Physical and Performance Requirements

ASTRONAUT MANEUVERING UNIT PHYSICAL AND PERFORMANCE REQUIREMENTS	
Weight (lbs.)	190
Volume (ft.^{3})	20
Dimensions (ft.)	2 x 2 x 5
Support equipment weight (lbs.)	60
Support equipment volume (ft.^{3})	3.4
LSS/propellant tank weight (lbs.)	75
Propellant,gas	Oxygen
Regulated pressure to thruster (psia)	165
Power (watts)	330 (700 peak)
Data Requirements (bits/sec)	5000 (3000 min.)
• Voice	Yes
• TV Film	Yes

Initial AMU evaluation maneuvers will be conducted while the astronaut is tethered to the parent spacecraft. Untethered maneuvers will follow but will be constrained to the close proximity of the spacecraft. AMU EVA will be performed during daylight hours early in the experiment programs and will be extended later to include night conditions. Preliminary inflight maneuvering tasks for the tethered and untethered modes of evaluation are defined on the following page (p. 3-90).

3.4.3.8 Maneuverable Work Platform (MWP)

The MWP consists of four basic elements: (1) a forward control module, (2) an aft module, (3) a removable tools/spares module, and (4) a collapsible cargo frame. These four elements allow the MWP to take on three basic configurations: (1) a minimum configuration, containing only the fore and aft modules; (2) a nominal configuration containing the fore, aft, and tools/spares module; and (3) an expanded configuration, where the cargo frame replaces the tools/spares module. Extending along each side of the forward module are hinged "running boards" which act as scaffolds at the worksite. Figures 3-36 and 3-37 illustrate the three configurations (ref. 3.26).

The forward control module contains all of the flight controls and displays and the controls for the anchoring/grappler arms. Three of these arms are arranged in a triangular pattern on the forward face of the module. In addition, radar antennas, RCS thrusters, a circuit breaker panel, an emergency stub antenna, work lights, and colored running lights are provided. An environmental control system/life support (ECS/LS) compartment is anchored to the

AMU INFLIGHT MANEUVERING TASKS	
TETHERED MODE	UNTETHERED MODE
• Stabilize; orient to proper attitude, and translate to end of 200 ft. tether. • Retrothrust prior to reaching end of tether. • Stationkeep, maintaining attitude relative to spacecraft. • Orient (translate to spacecraft). • Retrothrust (make terminal velocity and attitude corrections). • Dock at work platform. • Translate to 100 ft. from spacecraft. • Induce external force and evaluate recovery. • Translate to spacecraft and terminate experiment.	• Stabilize; orient to proper attitude, and translate to a point within 200 ft. of spacecraft. • Stationkeep, maintaining attitude. • Orient; begin translation to spacecraft work platform. • Perform midcourse attitude and velocity variations. • Retrothrust, and dock at work platform. • Transfer 200 lb. mass from work platform to a point within 200 ft. of spacecraft and return. • Translate to a point 100 ft. from spacecraft. • Induce external force and evaluate recovery. • Begin translation to spacecraft. • Perform midcourse attitude and velocity variations. • Retrothrust and dock at spacecraft.

module base and incorporates body restraints for the crewman.

The top surface of the ECS/LS compartment provides a mount to secure the crewman's Portable Life Support System (PLSS) AMU, which is used to man the MWP from the parent spacecraft.

The aft module supports the aft grappler, the aft propulsion thrusters, and an extendible antenna. This antenna, which is controllable in azimuth and elevation, can be extended to a length of 20 ft. to maintain line-of-sight communication with the parent spacecraft around an intervening work site.

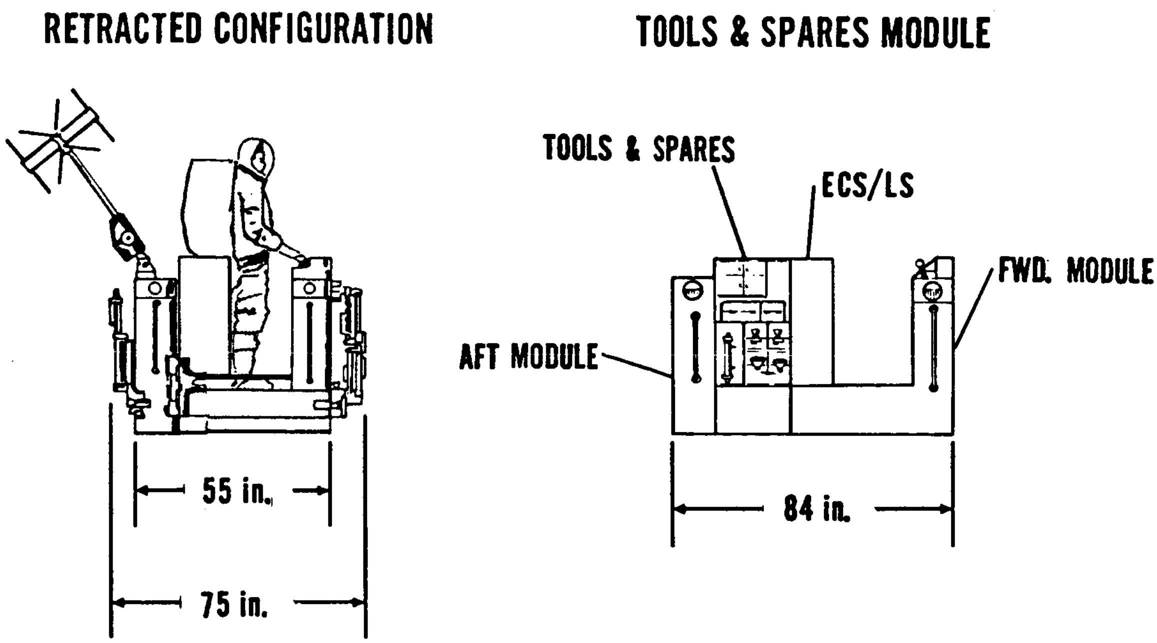


FIGURE 3-36: Maneuverable Work Platform (MWP) in the Retracted and Tool/Spares Configuration

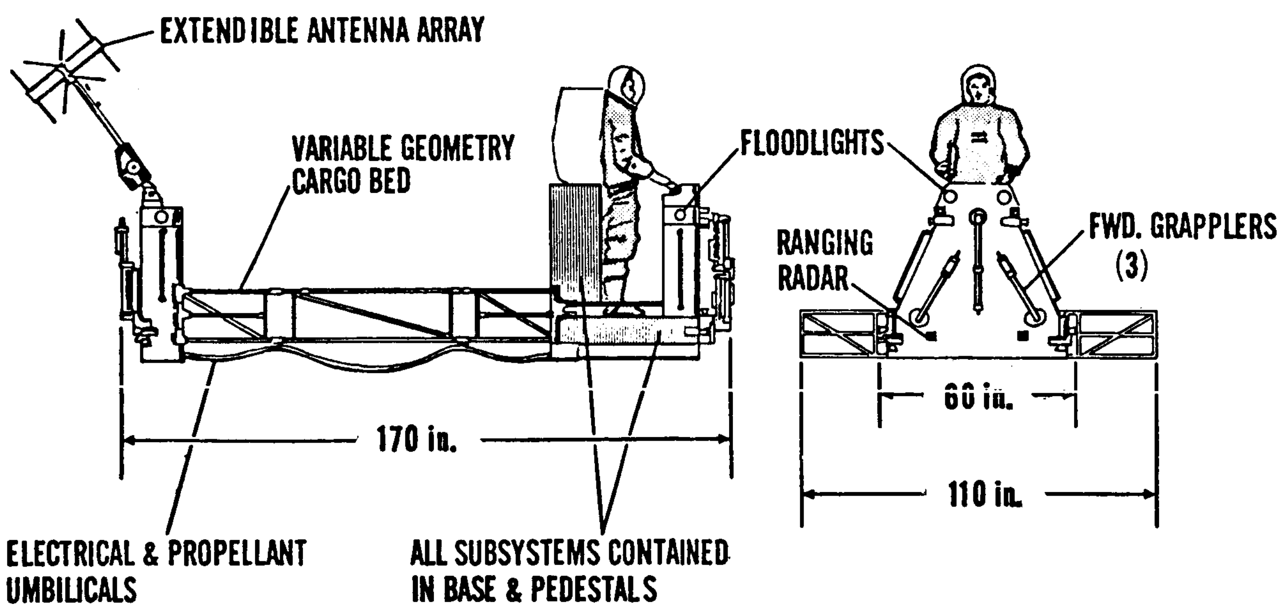


FIGURE 3-37: Maneuverable Work Platform in the Extended Configuration

The tools/spares module is designed in two sections with spare parts bins below and the tool box above. Covers for the tool compartment hinge to provide access; the upper covers form tool racks and the lower ones serve as work surfaces when open. The upper center panels of the tool bench serve for mounting gauges, meters, test plugs and jacks for diagnostic and check-out equipment. The tool box will be accessible from either side, with the crewman restrained in a standing attitude on the "running boards".

The variable-geometry cargo frame is assembled without tools by means of quick-disconnect structural joints. The frame is made of interchangeable truss sections fabricated from welded aluminum tubing. Each section terminates in one half of a sleeve-lock structural joint capable of transmitting structural loads in all directions. With the removable side sections inserted, the frame can be made approximately 100 in. square. Removal of these sections shortens the frame to 50 inches long.

The MWP displays fall in two primary categories: Extravehicular Referenced Information (ERI) and Intravehicular Referenced Information (IRI). The ERI group pertains to the display of information required by the crewman to perform the flight control functions. The IRI is concerned with the status of on-board systems. ERI parameters required for display in performing MWP missions are range and range rate. IRI requirements are derived from subsystem functions which have implications relative to mission performance or mission safety. These displays are subdivided into alerting and continuous displays. They provide information for several important parameters relating to: (1) the electrical power system; (2) propulsion, stabilization and control; (3) communications; (4) the docking and anchoring grapplers; and (5) environmental control and life support. Available MWP performance requirements are listed in Table 3-20.

TABLE 3-20: Maneuverable Work Platform Performance Requirements

MANEUVERABLE WORK PLATFORM PERFORMANCE REQUIREMENTS	
Weight (lbs.)	1600
Volume (ft.^{3})	140
Dimensions (ft.)	5 x 4 x 7
Support equipment weight* (lbs.)	2006
Support equipment volume* (ft.^{3})	186
Propellant, gas	Oxygen
Power (watts)	580 (980 peak)
Data requirements (bits/sec)	8000 (5000 min.)
• Voice	Yes
• TV Film	Yes

*Includes weight and volume for AMU, teleoperator system, camera and data displays.

Flight control evaluations of the MWP will initially be conducted untethered in close proximity to the spacecraft. Remote maneuvers will then be performed to permit evaluation of guidance, navigation, and rendezvous operations. As in the AMU evaluation program, the MWP experiment will be performed during daylight and night side conditions. Preliminary inflight maneuvering tasks for the close proximity and remote modes of evaluation are defined on the following page (p. 3-94).

3.4.4 Manual Cargo Transfer

Manual cargo transfer, as defined by the EVA Guidelines document, is the unassisted movement of supplies and equipment from vehicle(s) point to point, while attached to and accompanied by the crewman along the entire transportation route. The cargo may be hand held by the crewman and/or attached by rigid or flexible mechanical devices carried with the crewman. Manual cargo transfer in the orbital extravehicular environment utilizes handrails and handholds when the cargo transfer requirements are confined to one vehicle or to docked vehicles. The manual transfer of cargo between close proximity undocked vehicles may be accomplished when vehicle to vehicle tethers are employed.

The transfer of cargo (relatively small experiment packages and cameras) during the Gemini and through the Apollo 16 orbital EVA missions was accomplished by totally manual operations. The equipment transferred was usually attached to the crewman's pressure suit by a tether located on the wrist or near the waist. The crewman utilized handholds and handrails to retrieve and transfer the equipment to the vehicle stowage location. The limited size, mass and volume of cargo handled and transferred on orbital EVA missions through Apollo 16 has precluded the necessity for cargo transfer aids.

Various conceptual methods have been defined, and ground based simulations have been conducted to evaluate manual cargo transfer techniques. The support equipment associated with the techniques consists of personnel harnesses, backpacks, waist belt/tethers, and manually adjustable frames attached to the cargo unit and the crewman. Body-mounted harness configurations include a single package mounted in the lower abdominal area (front) or two side-mounted packages attached to each leg in the mid-thigh region and near the waist. Developers of the body harness concepts indicate that the front package size should be limited to 15 inches by 15 inches by 30 inches and the mass to 100 pounds to avoid obstructing mobility. The dual side-mounted packages should not exceed 12 inches by 12 inches by 30 inches, and the mass should be limited to 75 pounds each (ref. 3.3).

Several backpack and waist belt/tether concepts were developed and preliminary cargo transfer evaluations conducted. These devices included both rigid and flexible construction, which allowed the crewman to secure the cargo to his back or around the waist area. Evaluations of these concepts were limited and the mass and size restrictions for cargo to be transferred were not definitely established.

MWP INFLIGHT MANEUVERING TASKS	
CLOSE SPACECRAFT PROXIMITY	REMOTE MODE
• In retracted configuration, stabilize, orient to proper attitude, and translate to a point approximately 200 ft. behind parent spacecraft. • Stationkeep, maintaining attitude. • Orient; begin translation to spacecraft. • Perform midcourse attitude and velocity corrections. • Retrothrust, and dock at spacecraft work platform. • Undock and translate to a point 100 ft. behind spacecraft. • Induce external force and evaluate recovery. • Translate to spacecraft, and dock using forward grapplers. • Assemble MWP to the extended configuration. • Undock and transfer 500 lb. mass to a point approximately 200 ft. behind spacecraft; then stationkeep. • Induce external force and evaluate recovery. • Translate to spacecraft, performing midcourse attitude and velocity corrections. • Dock at spacecraft with forward grapplers. • Reassemble MWP to retracted configuration.	• In retracted configuration, stabilize, orient, and translate to a remote object approximately 1.3 mi. (statute) behind spacecraft. • Retrothrust without contacting object. • Stationkeep; maneuver around the object for inspection. • Reorient and begin translation to spacecraft. • Perform midcourse attitude and velocity variations. • Retrothrust and dock at spacecraft work platform using forward grapplers. • Assemble MWP to extended configuration. • Transfer 500 lb. mass to remote position approximately 1.3 mi. (statute) behind the spacecraft and return. • Dock with spacecraft and reassemble MWP to retracted configuration.

A manually adjustable frame has been considered for manually handling cargo of irregular shapes as well as geometric configurations. The concept consists of an adjustable frame which is attached to the package being transferred and to the extravehicular crewman. By extending one frame section a greater amount than its counterpart, the center of mass could be maintained within acceptable limits with respect to the crewman/cargo combination. The adjustable cargo-handling frame consists of a central section with telescoping segments which can be extended outward, lower cargo attach members which rotate forward and lock, upper stabilization members, and adjustable cargo attach straps to secure the frame and cargo to the EVA crewman. A pair of ankle-foot harnesses are worn by the crewman which, in addition to waist attached points, provide cargo restraint and adequate cargo stabilization during transfer. Mass and size limitations of cargo that can be transferred with the adjustable frame have not been established (ref. 3.3).

Since there was not a requirement for transfer aids other than tethers and handrails, none of the manual cargo devices or concepts discussed above have been used on Orbital EVA missions through Apollo 16. The above concepts were presented to relate information concerning areas that have been considered and that may find application in future manned space missions. Development of manual cargo transfer equipment is considered well within the present state-of-the-art with no unique technological problems anticipated.

3.4.5 Assisted Cargo Transfer

There have been a number of cargo transfer aids designed, developed, and tested to mechanically assist the crewman in handling and transporting equipment in a zero-gravity environment. The transfer assist devices which presently appear to be strong candidates for future EVA application are the rigid rail devices (trolleys), tubular extendible members, and "endless clothesline" units. For Skylab extravehicular operations, tubular extendible members (Film Transportation Booms - FTB) are provided as the prime cargo transfer systems, and clothesline units are provided as backup systems.

3.4.5.1 Cargo Transfer Rails

Several types of rail or guide systems have been considered for extravehicular cargo transport between points on a vehicle or between docked vehicles. These systems consist of single or dual rails and a trolley type pallet for attaching cargo. The use of a single or dual (parallel) rail system is

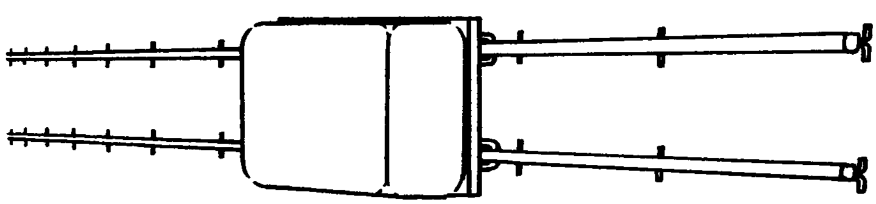


FIGURE 3-38: Dual Rail Cargo Transfer System Concept

primarily dependent on the size and mass of cargo to be transferred. The rail systems have the option of being powered (motor driven), manually actuated by or continuous-loop tether lines, or pushed/pulled by the crewman. An illustration of a simple dual rail cargo transfer system is shown in Figure 3-38. Numerous systems or families of guiderails and pallet devices are possible and present no unusual technological problems in their design and development. The rail/pallet cargo transfer concept has not been used on flights to date; however, several system prototypes have been fabricated and evaluations conducted (ref. 3.9).

3.4.5.2 Tubular Extendible Members

Tubular extendible members of various sizes and configurations have been used as antennas, instrument carrying booms, gravity gradient stabilization rods, structural elements, etc. on the Apollo, Gemini, Mercury and earlier aerospace programs. The tubular extendible members consist of a continuous strip(s) of resilient spring metal which has been treated for maximum flexibility and which possesses various unfurled characteristics. Storage of the member(s) is accomplished by coiling the metal strip around or into a cylindrical drum (Figure 3-39) which rotates for extension and retraction, either by means of a motor drive or hand crank. Push-pull and self-extendible concepts are also available (refs. 3.27 and 3.28).

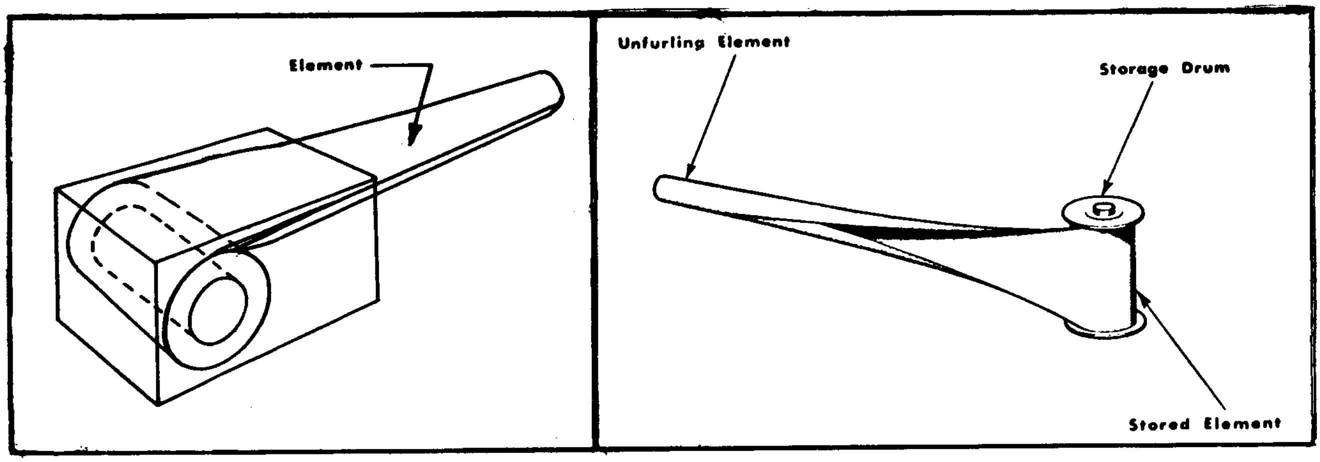


FIGURE 3-39: Tubular Extendible Member Operating Principle

The cylindrical drum diameter is chosen such that the elastic limit of the metal strip or element is not exceeded when coiled on the drum. As a result, no permanent strain is introduced in the element. The strength characteristics of the unfurled element is provided by the element configuration, the amount of overlap, and the number of elements. The element is free of stress in its unfurled shape. Several unfurled boom shapes are available depending on the particular application requirements. Three of the most used boom element configurations are shown in Figure 3-40.

The principle upon which the tubular extendible members function provides the advantage of being able to operate over relatively large distances with equipment which required little stowage volume.

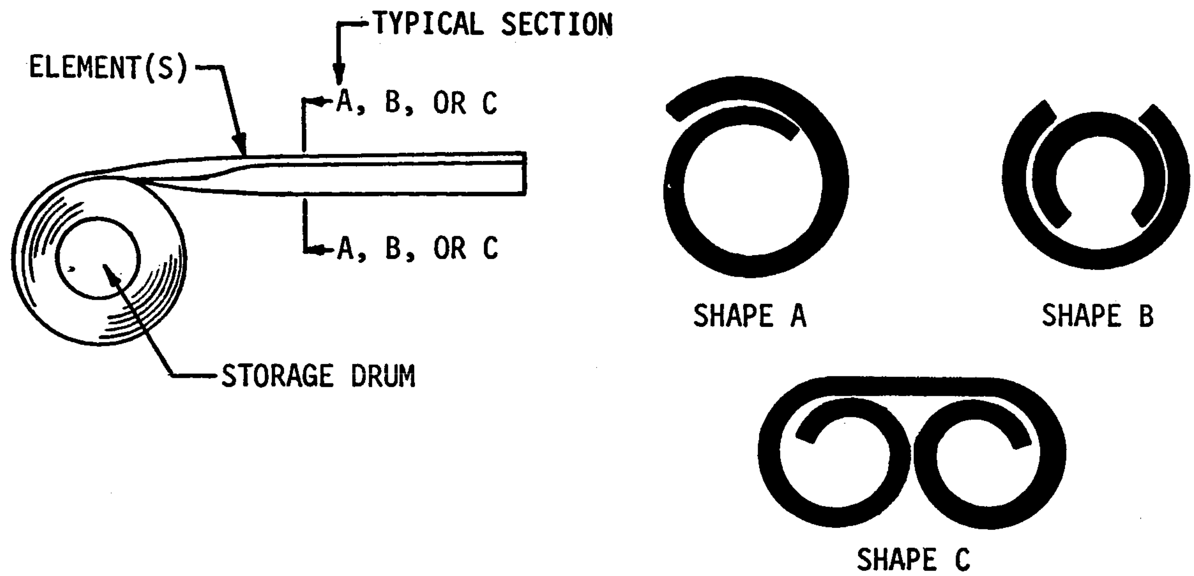


FIGURE 3-40: Unfurled Tubular Extendible Member Configuration

Two extendible members, referred to as Film Transportation Booms (Figure 3-41), will be used during the Skylab EVA missions to transfer cargo (film magazines) from the Apollo Telescope Mount experiment canister to the Airlock Module. The booms are mounted in receptacles outside the vehicle and are prealigned to receive cargo from two separate EVA workstations. The booms are electrically driven with a backup manual actuation system. Each boom can be removed from its receptacle by the EVA crewman and replaced with a spare boom. The spare boom is also stored outside the vehicle and is readily accessible to the EVA crewman.

The cargo is attached to a fixed boom hook which secures and restrains the cargo movement sufficiently to restrict momentum buildup during transfer operations. The cargo is manually loaded and unloaded at the EVA workstations. The characteristics of the Film Transportation Boom used on Skylab are shown in Table 3-21 (ref. 3.9).

3.4.5.3 Clothesline Cargo Transfer Technique

The clothesline cargo transfer system essentially consists of a continuous loop, highly flexible line, pulleys or rings, hooks/devices to secure the clothesline to the vehicle, and of devices to attach the cargo to the clothesline. Devices for cargo attachment to the clothesline system usually consist of simple tether type hooks attached directly to the cargo, or they may incorporate a cargo frame. A cargo frame attached to the clothesline, with clamping devices and guide units, provides two-axis stability.

The contingency cargo transfer systems supplied on the Skylab Program consist of two endless clothesline units. The transport lines are driven through

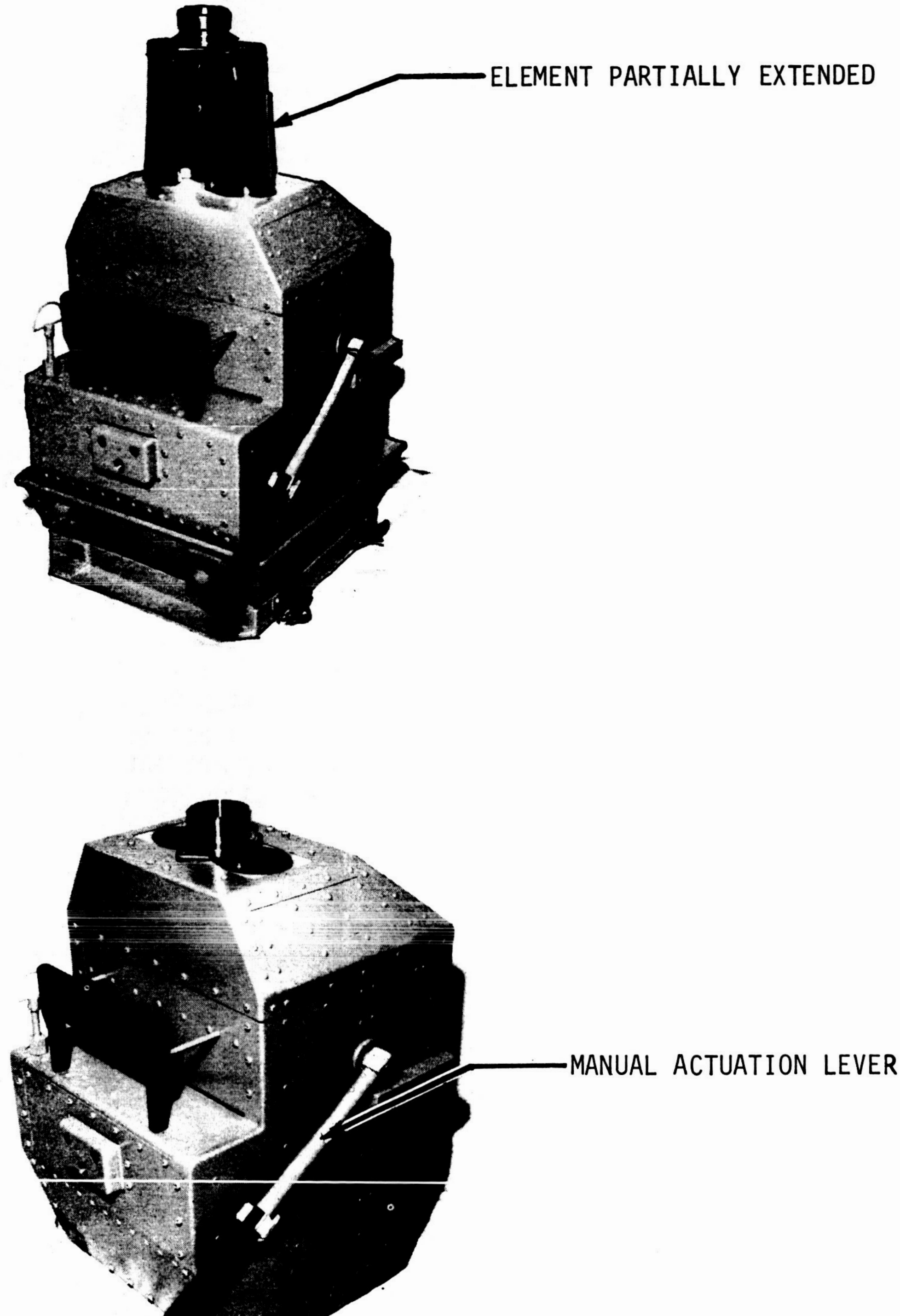


FIGURE 3-41: Skylab Film Transportation Boom

TABLE 3-21: Skylab Film Transportation Boom Characteristics

SKYLAB FILM TRANSPORTATION BOOM CHARACTERISTICS	
Weight (lb.)	85 (Approx.)
Volume (in.^{3})	3900. (Approx.)
Dimensions (in.)	25 x 13 x 12 (Approx.)
Boom Diameter (in.)	1.67 (Each Loop)
Element Thickness (mil)	7.5
Boom Extension (ft.)	28.6 (Nominal)
Element Configuration	Figure 8
Element Material	Beryllium Copper
Actuation Method	Electric or Manual
Extension Rate (in./sec.)	5
Retraction Rate (in./sec.)	5
Power (watts)	75 (extend or retract)
System Reliability	R = .9998

two rings that act as sheaves for the clothesline. Hooks are incorporated in the rings for attaching to points or booms supplied on the vehicle. Two additional hooks are included on the clothesline for attaching the cargo. A tensioning strap is included between the cargo attach hooks to maintain tautness in the system. The contingency cargo transfer clothesline carried aboard Skylab is shown in Figure 3-42. The Skylab clothesline system characteristics available during the development of this document are contained in Table 3-22 (ref. 3.9).

3.5 EVA WORKSITES

3.5.1 Introduction

A worksite is defined as a location where an EVA astronaut remains stationary for some period of time to perform specific operations. Unlike the hardware-oriented systems that have been discussed previously, the worksite is composed of, or supported by, a group of interdependent systems. Therefore,

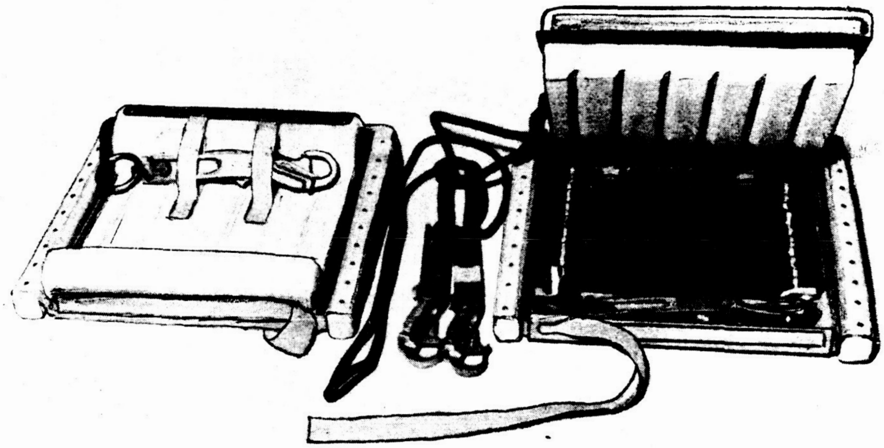


FIGURE 3-42: Skylab Contingency Cargo Transfer System (Clothesline) - Stowed Position

the technology used in developing a worksite is primarily concerned with integrating the hardware systems and operational procedures needed at the location to support a particular task. Once the task has been defined and the limiting constraints and guidelines have been identified, a selection of specific hardware systems and procedural options can be integrated to provide adequate worksite support.

3.5.2 EVA Worksite Classification

Two general classes of worksites can be identified: (1) prepared and (2) unprepared. A prepared worksite is one in which the site location and the EVA astronaut operations to be performed at the site are established during equipment design. The site contains all lighting aids, restraint systems, and control/displays required by the astronaut to perform worksite activities. Unprepared sites refer to the locations where an astronaut terminates translation activities to perform a planned EVA function. The location of the unprepared site may or may not be predetermined; if determined, it is selected by the astronaut during EVA. Examples of prepared and unprepared worksites for past and future design missions (through Skylab) are presented in Table 3-23.

3.5.3 EVA Worksite Requirements

Prepared and unprepared worksite development or worksite technology, beginning with the Gemini Program and continuing through the Skylab Program, has more or less generated a set of generally accepted worksite baseline

TABLE 3-22: Skylab Clothesline System Characteristics

SKYLAB CLOTHESLINE SYSTEM CHARACTERISTICS	
Weight (lb.)	-
Volume of Container (in.^{3})	46.2
Dimensions of Container (in.)	12.5 x 11.0 x 3.5
Extension Length (ft.)	28-33
Line Material	PBI
Line Diameter (in.)	-
Deployment Method	Manual
Actuation Method	Manual
Breaking Strength	-

requirements. Although the requirements were not baselined for a specific program, all of the worksites developed, thus far, have responded in some degree to this set of requirements. Table 3-24 presents these worksite-associated requirements (ref. 3.12).

3.5.4 Representative EVA Worksites

As previously indicated, a worksite is an integration of various systems. Unlike a crew protective system or life support system, it has no well defined performance, operational, or physical characteristics. The remainder of this section will briefly describe the following Skylab EVA workstations insofar as they are representative of the present status of worksite technology:

- Airlock/FAS Workstation (VF)
- Center Workstation (VC)
- Transfer Workstation (VT)
- Sun End Workstation (VS)

It should be pointed out that this is not an attempt to discuss, in depth, the operations that are to be performed at each workstation, or the design philosophy behind the development of each workstation. It should also be noted

TABLE 3-23: Summary of Prepared and Unprepared Worksites

MISSION	PREPARED WORKSITES		UNPREPARED WORKSITES
	WORKSITE	ACTIVITIES	ACTIVITIES
<u>Gemini</u>			
IV	Gemini Hatch	16mm camera installation. Umbilical guard installation.	
IX-A	Gemini Hatch	Handrail deployment. S-012 micrometeoroid package retrieval.	Velcro hand-pad evaluation.
	Adapter Section	Astronaut Maneuvering Unit (AMU) donning.	
X	Gemini Hatch	S-012 retrieval.	N_2 line disconnect. S-010 Micrometeoroite package retrieval at GATV. T-017 micrometeoroite experiment installed at GATV.
XI	Gemini Hatch	UV Stellar Photography.	Tether attachment.
	Adapter	Foot restraint evaluation.	
XII	Gemini Hatch	UV stellar photography. Synoptic terrain photography. Handrail deployment.	
	Target Docking Adapter	Tether attachment. Evaluation of work tasks. Retreival of S-010.	
	Adapter	Evaluation of work tasks.	
<u>Apollo</u>			
9	Command Service Module Hatch	Photography,	
	Lunar Module Hatch	Photography, sample retrieval.	
15	SIM Bay	Retrieve film from 24" panoramic and 3" mapping cameras. Inspect SIM Bay.	
	Command Service Module Hatch	Assist film retrieval, photography, manage umbilical.	
16	SIM Bay		
	Command Service Module Hatch		
17	SIM Bay		
	Command Service Module Hatch		
<u>Skylab</u>	VF: FAS Workstation	Film handling and loading, photography, umbilical management, sample retrieval.	
	VC: Center Workstation	Film retreival/replacement, umbilical management, photography.	
	VS: Sun End Workstation	Film retreival/replacement, umbilical management, photography.	
	VT: Transfer Workstation	Film handling and loading, photography, umbilical management.	

TABLE 3-24: Associated Worksite Requirements

STABILIZATION

- Type of Stabilization
  - Restraint
  - Handhold/foothold
  - Both restraints and hand/foothold
  - Cage
  - Portable or fixed
- Restraint Location
  - Waist
  - Foot
  - Other body attachment (chest, knee, etc.)
- Restraint Type
  - Rigid
  - Flexible
  - Rigidized
  - Retractable - spring loaded
- Handhold/Foothold Characteristics
  - Length
  - Hand/foot clearance
  - Location
  - Relation to restraints
- Restraint Fastener
  - Quick disconnect
  - Positive feedback of activation
- Restraint Adjustments
  - Disconnect/connect
  - Tighten/loosen
- Safety Considerations
  - Backup tether
  - Restraints - footholds don't themselves become hazards

EQUIPMENT MOUNTING

- Umbilical Secure
- Temporary Storage of Equipment
  - Tools
  - Samples
  - Data recording equipment

FORCE

- Type of Force
  - Sustained
  - Impulse
- Direction of Force
  - Up/down
  - Lateral
  - Fore/aft
  - Rotational
- Magnitude of Force
- Counterforces

SITE ACTIVATION

- Type of Activation
  - Remote
  - Local - pre-entry
  - Local - post-entry
- Operations
  - Activation of light sources
  - Configuration of structures
  - Selection of operational modes
  - Decision to enter site

SITE LOCATION

- Type of Location
  - Whole body in free space
  - Body partially in free space - partially in confined space
  - Within unpressurized vehicle
  - Transportable site - as an end of sepentuator or portable workstation
- Relationship to Vehicle
  - Immediately adjacent to vehicle structures
  - Removed from vehicle
  - Line of site or hidden

SITE ENTRY

- Clearance of Entry
  - Whole body
  - Limb
  - Encumbered - unencumbered
- Provisions for Emergency Escape
- Safety Hazards Around Entry
  - Protuberances
  - Moving parts
  - Unstable structures
  - Sensitive areas
- Visibility of Entry
  - Color coding of translation aids - handholds, foot restraints
  - Lighting of entire entrance
  - Lighting of worksite within entry
- Body Orientation to Entrance at Entry
  - Always head first or frontal
  - Sideways entry is acceptable if entrance and worksite are in the field of view during actual entry
- Umbilical Dynamics

LIGHTING

- Type
  - Body mounted
    - Wrist
    - Helmet
    - Chest
  - Hand held
  - Removable
  - Fixed
- Number of Lights
- Location of Lights
- Field of View
- Brightness
- Avoidance of Glare
- Color
- Adjustments
  - Direction
  - Brightness
  - Field of view size
  - Number of lights
  - Location
- Power Requirements

ASTRONAUT/WORKSITE INTERFACE

- Type of Site
  - Unconfined
  - Semiconfined
  - Confined
    - Limbs
    - Whole body
      - body clearances
      - presence of protuberences
- Astronaut Orientation
  - Body axis parallel to main axis of site
  - Body axis perpendicular to main axis of site
  - Body axis offset from main axis of site

MOBILITY

- Motions Required in Worksite
  - Whole body
    - Rotational
    - Translational
      - lateral
      - front-back
      - up-down
      - twisting
  - Limbs
    - Direction of motion
    - Range of motion
- Extent of Motion
- Frequency of Motions

CONTROL/DISPLAY

- Nominal Operational
  - Location
  - Size
  - Type
  - Operating characteristics
  - Number
  - Illumination
  - Labelling
  - Orientation
  - Relation of controls to displays
- Contingency Operation
  - Alarms
  - Malfunction detection
  - Fault isolation
  - Checkout

SITE OCCUPANCY

- Duration
- Frequency - number of times during EVA and during one mission
- Number of similar sites

that the figures within this section are somewhat dated; however, the work envelopes that appear have not been significantly altered by later hardware component modifications. See Section 2.2.2 for the Skylab EVA mission definition and a listing of the hardware components associated with each of the above EVA worksites.

3.5.4.1 Skylab Airlock/FAS Workstation (VF)

The Airlock/FAS Workstation (VF) is located immediately adjacent to the Airlock Module EVA hatch (see Section 3.3). During EVA, the first EV crewman translates to, ingresses, and remains in the Airlock/FAS primary foot restraints throughout the remainder of the EVA. This worksite was designed primarily for support of cargo transfer and umbilical management operations and also to support various contingency operations. See Figure 3-43 for a view of the Airlock/FAS Workstation and several of its major hardware components.

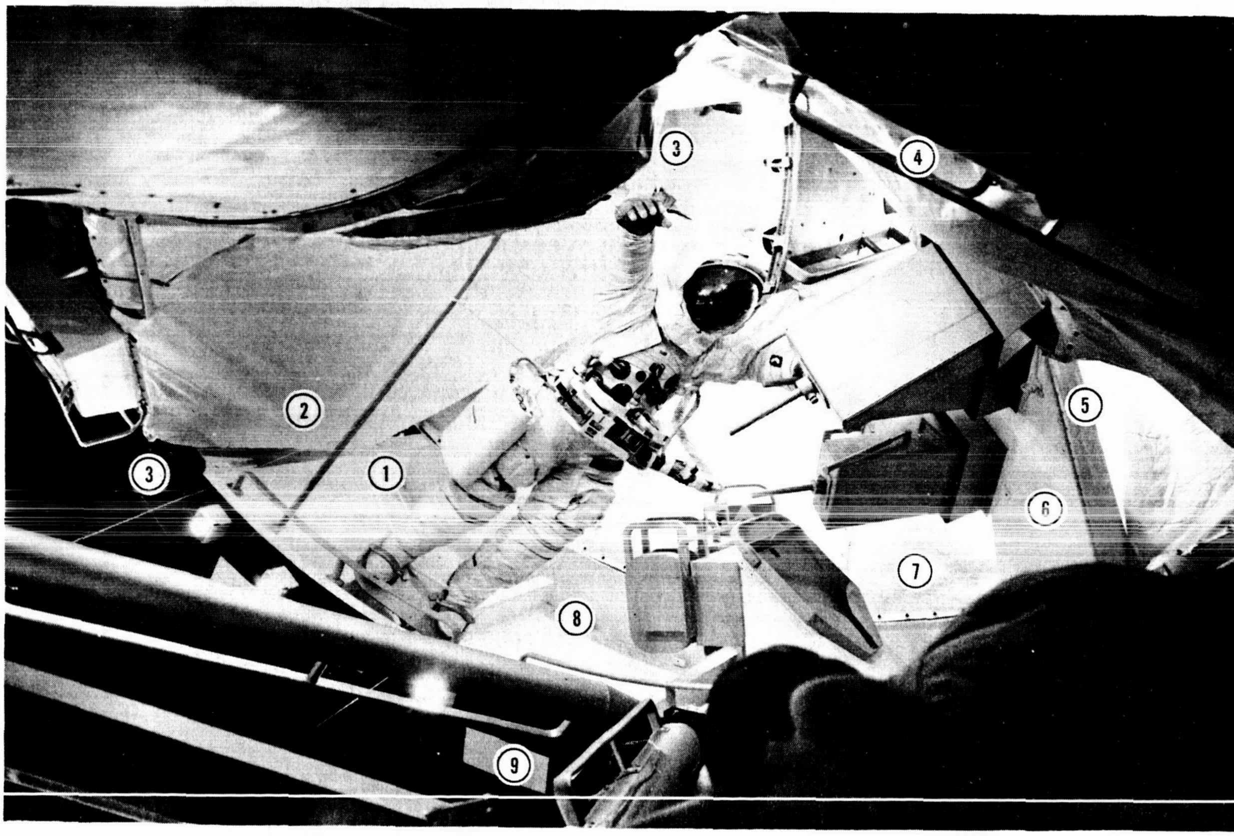


FIGURE 3-43: Airlock/FAS Workstation (VF). Note: (1) Primary Foot Restraints, (2) Handrails, (3) EVA Lights, (4) Airlock Hatch, (5) Sun End Workstation Cargo Transfer Boom, (6) Center Workstation Cargo Transfer Boom, (7) Sun End Cargo Temporary Stowage Receptacle, (8) Center Workstation Cargo, and (9) Translation Rail To ATM Center Workstation.

3.5.4.2 Skylab Center Workstation (VC)

The center Workstation (VC) is located on the Apollo Telescope Mount (ATM). During EVA, the second EV crewman egresses the Airlock EVA hatch, translates to the Center Workstation, and ingresses the primary foot restraints. This EV worksite was designed to support the manual retrieval/replacement of four film packages, to provide an alignment capability of the ATM canister in support of the Sun End Workstation operations, and to support contingency cargo transfer operations. See Figure 3-44 for a view of the Center Workstation and several of its major hardware components.

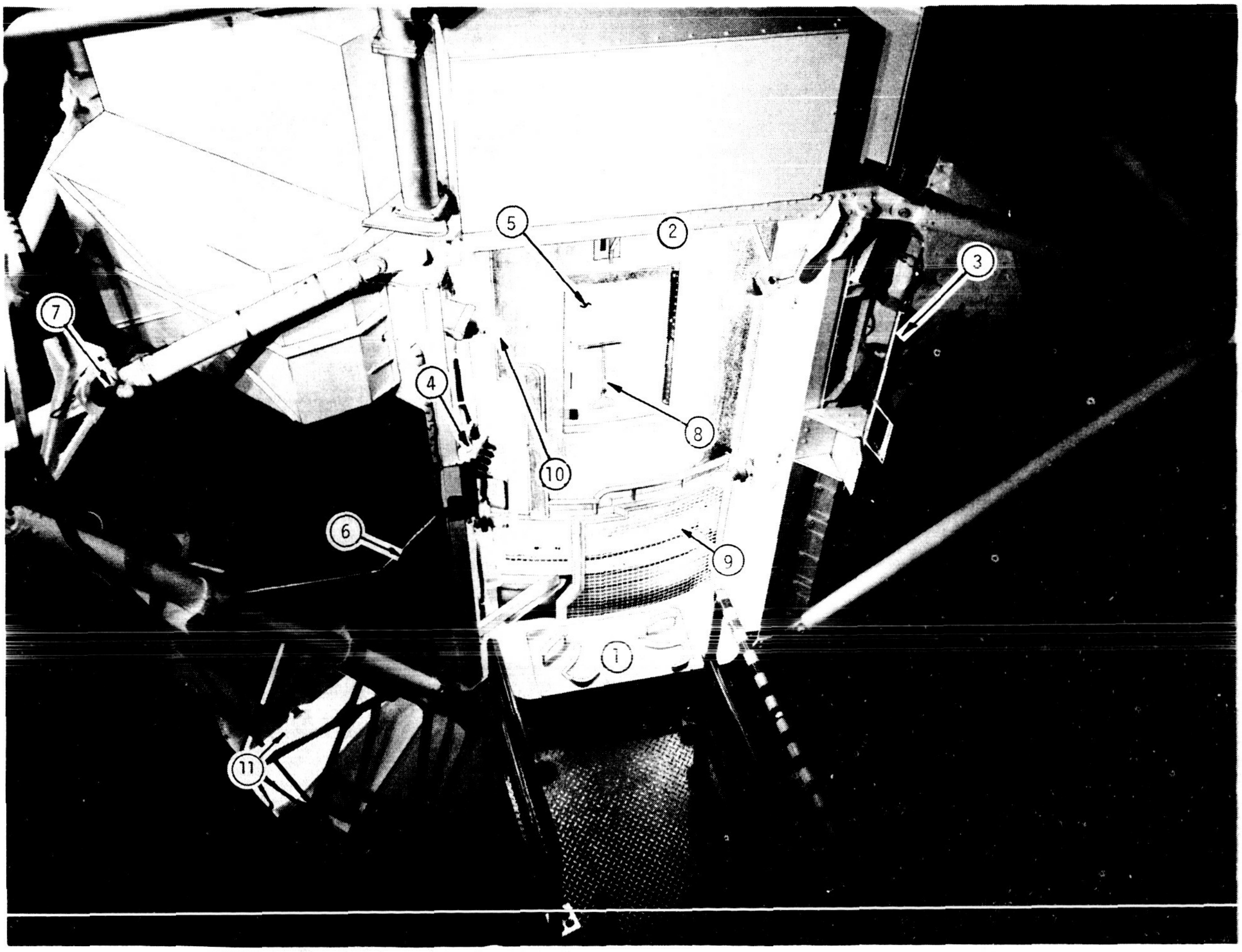


FIGURE 3-44: Center Workstation (VC). Note: (1) Primary Foot Restraints, (2) ATM Canister Alignment Indicator, (3) Contingency Transfer Interface Bracket, (4) ATM Canister Roll Control Panel, (5) Film Package Access Door, (6) Translation Rail to/from Dual Translation Rails, (7) EVA Translation Path Light, (8) Access Door Handle, (9) VC Handrail and Protective Grid, (10) VC Lights, and (11) Transfer Workstation Light.

3.5.4.3 Skylab Transfer Workstation (VT)

Once the Center Workstation operations are completed, the second EV crewman translates along the dual rails to and ingresses the Transfer Workstation (VT). This worksite primarily supports Sun End cargo transfer and handling. Sun End cargo is transferred from the Airlock/FAS Workstation (VF) to the EV crewman at the VT. He, in turn, removes the cargo from the transfer device and places it in the Sun End primary stowage location. The astronaut then translates to the Sun End Workstation. Once the Sun End Workstation operations are complete, the return cargo is transferred from the VT to the VF. The Transfer Workstation is also designed to support contingency transfer operations. See Figure 3-45 for a view of the Transfer Workstation and several of its major hardware components.

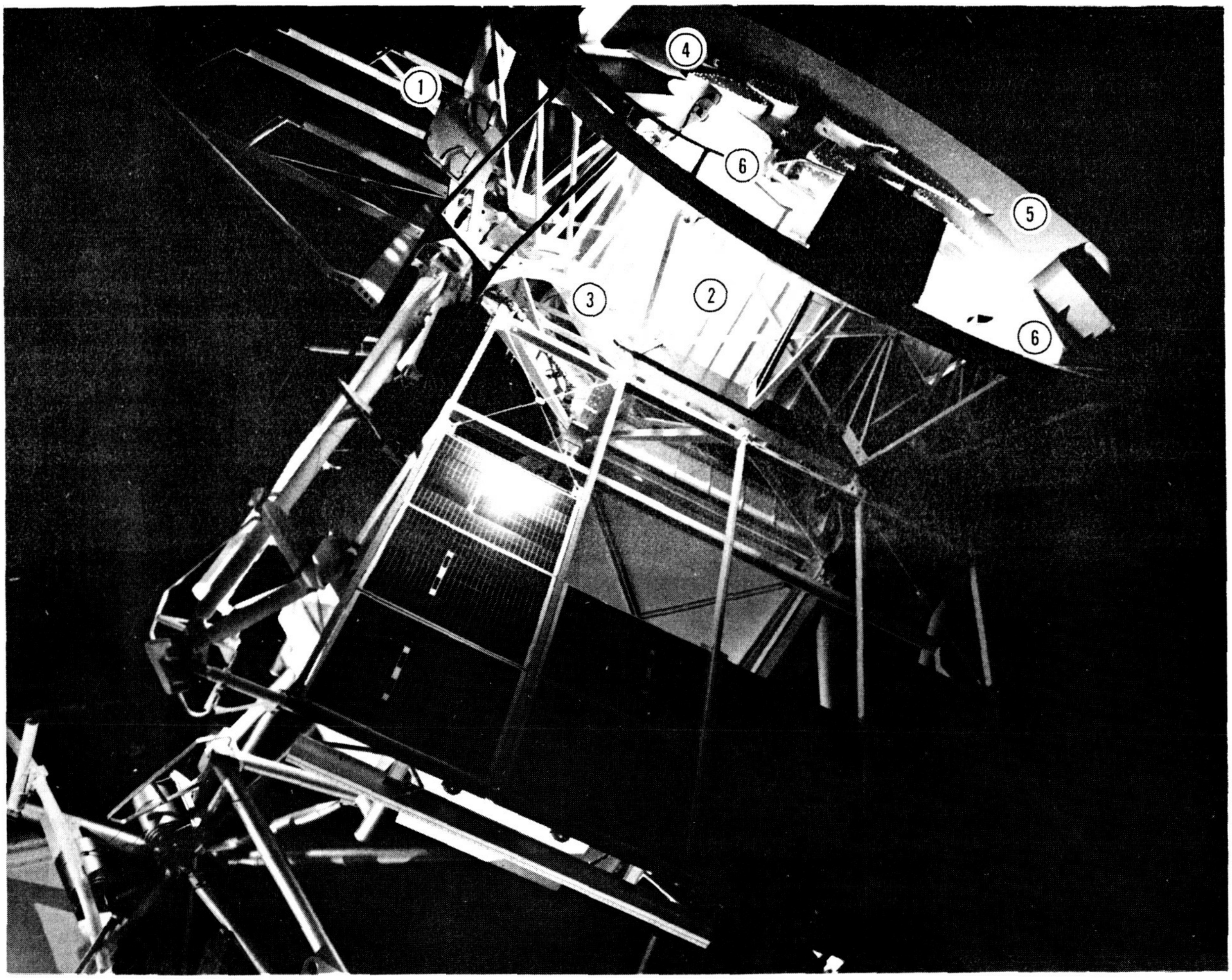


FIGURE 3-45: Transfer Workstation (VT). Note: (1) Primary Foot Restraints, (2) Transfer Workstation Light, (3) Dual Translation Rails, (4) Sun End Primary Cargo Stowage Receptacle, (5) Sun End Cargo Temporary Stowage, and (6) Sun End Workstation Lights.

3.5.4.4 Skylab Sun End Workstation (VS)

Once the Transfer Workstation operations are completed, the second crewman translates to and ingresses the Sun End primary foot restraints. (The Sun End Workstation is not in a line-of-sight with the Airlock/FAS Workstation which is approximately 30 feet away.) This workstation was designed to support the manual retrieval/replacement of two film packages. See Figure 3-46 for a view of the Sun End Workstation and several of its major hardware components.

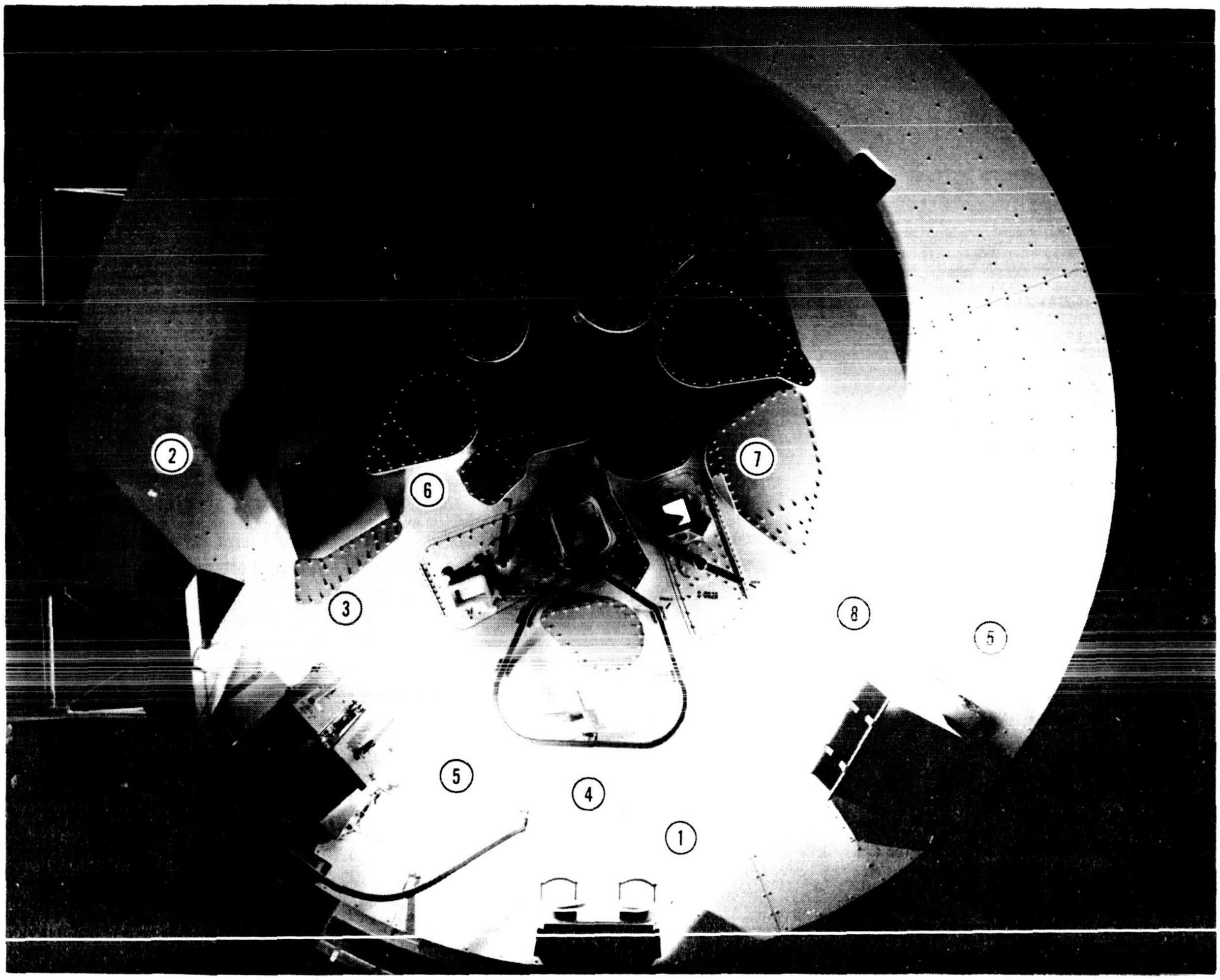


FIGURE 3-46: Sun End Workstation (VS). Note: (1) Primary Foot Restraints, (2) Contingency Transfer Interface Bracket, (3) Sun End Cargo in the Primary Stowage Receptacle, (4) Handrails, (5) Sun End Workstation Lights, (6) S-082B Film Package Access Door, (7) S-082A Film Package Access Door, and (8) Sun End Cargo Temporary Stowage.

3.6 EXTERNAL LIGHTING

3.6.1 Introduction

During their orbit around the earth, most spacecraft are subjected to illumination of varied brightness and intensity due to their position relative to the sun, earth, and moon.

The visual environment encountered in orbit can affect EVA crewman performance. The environment in each situation is often one where intense illumination and extreme contrasts are the prevailing visual conditions. Table 3-25 provides a range of contrasting luminance for comparison of the intensities to which the eye can be exposed (if it is not protected) in the orbital EVA environment.

TABLE 3-25: Contrasting Luminances

	OBJECT VIEWED	VIEWED FROM	LUMINANCE
Celestial Bodies	Sun	Outside earth's atmosphere	7×10^8 ml
	Earth	Outside earth's atmosphere	4.4×10^8 ml
	Earth (dayside)	Earth orbital space	4.3×10^3 ml to 9.4×10^3 ml
	Full Moon	Earth	8×10^2 ml
Common Objects	TV Screen		1×10^1 ml
	White Paper (in good reading light)		2×10^1 ml

For approximately three-quarters of the earth orbit, the spacecraft will be illuminated either singularly or by a combination of lights from the sun, earth, moon and stars. Figure 3-47 indicates the various illumination environments which might be encountered by a spacecraft in orbit around the earth and moon and those which might be encountered in transit between the two orbits. The "light" side of the orbit will require the EVA crewman to wear the EVA helmet visor for protection against the high intensity of the light source.

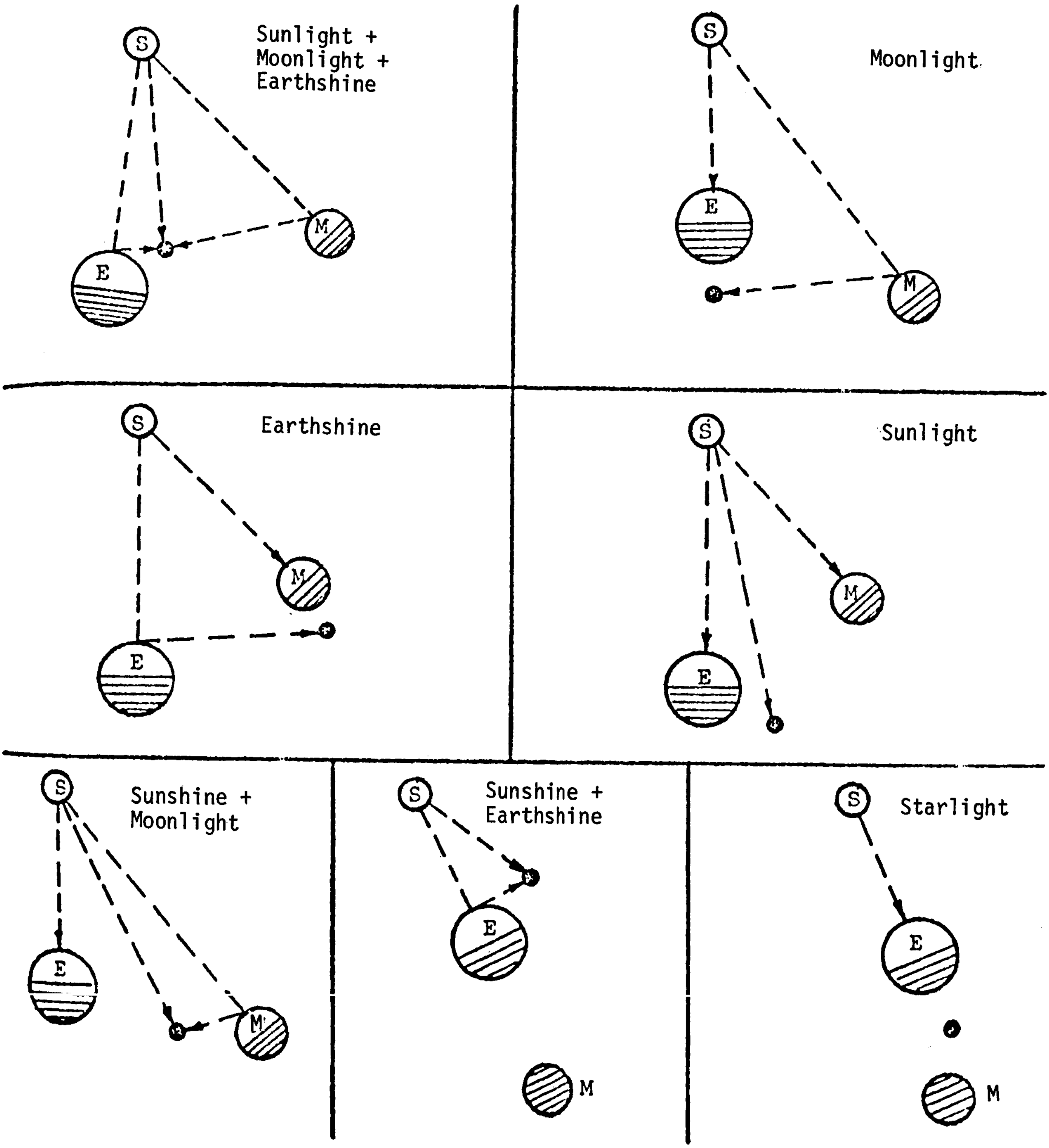


FIGURE 3-47: Spacecraft Illumination Environments (Earth/Moon)

The complex illumination difficulties in configuration identification in space can create visual problems for the EVA crewman, such as difficulties in shape determination and distance judgment. A summary of several of the solar illumination characteristics is presented in Appendix B. The solar illumination characteristics as described in the appendix will, of course, remain unchanged, but the effects on differently configured space vehicles will vary appreciably.

For the remaining one-quarter orbit, the spacecraft will be in near darkness and will require artificial lighting. The light levels required for external "dark side" illumination during EVA operations are discussed in the following sections.

3.6.2 External Lighting Specifications

The NASA Manned Spacecraft Center has developed general specifications for spacecraft lighting (ref. 3.29) which identify the basic design considerations and criteria which the designers should employ when designing the lighting from various illumination sources for the crew stations and compartment areas of aerospace vehicles. These specifications include external lighting requirements for the purpose of aiding lighting design of search and detection, rendezvous and docking, extravehicular activity and landing lights. The illumination specifications established by the document for extravehicular operations are shown below:

- Lamp - The EVA worksite light shall be incandescent or any other type lamp meeting the illumination requirements.

- Intensity - The EVA light used to illuminate the surface of the vehicle shall have a luminous intensity (candle power) sufficient for the crewmen to perform their tasks. The brightness of the transfer routes shall be greater than 1 ft. lambert, and the brightness of workstations shall be 5 ft. lamberts or greater. The measurement shall be made off the vehicle surface at the visual interface.

3.6.3 Skylab EVA Lighting

Designing an effective lighting system for Skylab EVA necessitated identification of all cluster components that must be seen by either EVA astronaut. The number and placement of luminaires required taking into consideration the viewer position relative to the object to be viewed, the impact on mission success of not seeing an object, and any moving object which, through casting shadows, interferes with viewing.

If failure to see certain objects can cause a "life" or "mission critical" situation, sufficient light must be provided by two or more artificial sources for redundancy. Luminaires must be placed such that the EVA crewman, during his movements, does not receive excessive glare from lamps and does not shadow objects which must be seen for EVA task performance.

Through simulation activity on full scale Apollo Telescope Mount (ATM) mockups, the type, number, and placement of luminaires for providing necessary lighting were established. These lighting requirements are presented below (ref. 3.9).

- Light illumination
  - Min. 2.0 ft. lamberts for translation routes
  - Min. 5.0 ft. lamberts at workstations
- Light placement
  - AM EVA lights - five
  - DA EVA lights - six
  - ATM EVA lights - twelve
- Light wattage
  - 18.75 watts (incandescent)
- Light control
  - Panel 316 in lock compartment

A typical light assembly and the lamps used on Skylab are shown in Figure 3-48 and 3-49, respectively. Additional information and EVA light locations on Skylab are contained in Appendix B.

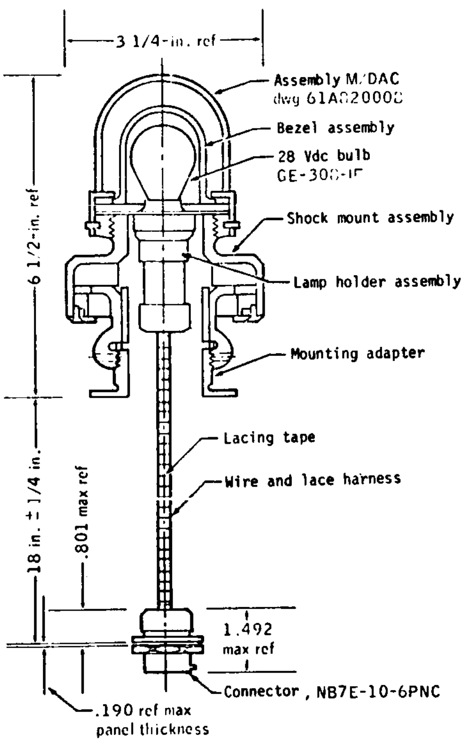
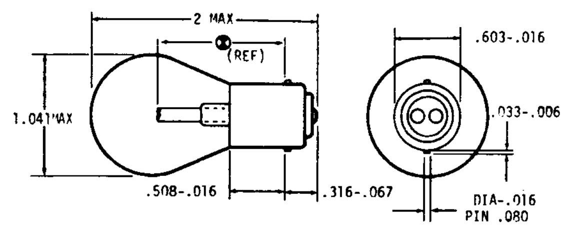


FIGURE 3-48: ATM EVA Light Assembly

ATM EVA LAMP SPECIFICATION



MS NUMBER	TRADE NUMBER	CANDLE POWER MAJOR FIL	CANDLE POWER MINOR FIL	DESIGN VOLTS	DESIGN AMPS MAJOR FIL	DESIGN AMPS MINOR FIL	LIGHT CENTER LENGTH ⊗	FIL CONST	AVG LIFE (HOURS)	FIIN
MS15584-16	308	21±15%		28.00	.67+8%		1-1/8	C-2V	300	155-7790

NOTE: 18.75 WATT INCANDESCENT LAMPS S-8 BULB, DOUBLE CONTACT, 21 CD ON EACH FILAMENT, BAYONET CANDELABRA BASE.

FIGURE 3-49: ATM EVA Lamp Specification

3.7 COMMUNICATIONS AND TELEMETRY

3.7.1 Introduction

The Gemini Program developed the initial personal communications and telemetry required in space exploration with the first system being carried aboard the Gemini IX.

Later, the Apollo Program established initial requirements for a space suit communications and telemetry system to accommodate an extravehicular astronaut. This requirement was expanded in early 1967 to include the capability for two extravehicular astronauts to explore the lunar surface.

In view of the advanced state of the Apollo design effort, a telecommunications system that would satisfy the following program and system design constraints was required. These system requirements were (ref. 3.30):

- No impact on the existing Lunar Module (LM) communications system design.
- Relay of continuous telemetry data to earth simultaneously from each of the two extravehicular astronauts.
- Minimum impact on the existing Portable Life Support System (PLSS).

3.7.2 Apollo

The original Apollo Space Suit Communications System (SCS) was designed to accommodate one extravehicular astronaut. Early in 1967, NASA established a requirement for an Extravehicular Communications System (EVCS) which would enable two astronauts to simultaneously explore the lunar surface. Included in this requirement was a telemetry subsystem to monitor the performance of the Portable Life Support System (PLSS), space suit performance, and body functions of each astronaut while on the lunar surface.

The Extravehicular Communications System (EVCS) provides for three modes of operation (ref. 3.7):

- Primary Mode - Including provision for telemetry signals and provision for simultaneous transmission and reception of voice for communications (duplex) between either of the two EVA astronauts and the space vehicle.
- Secondary Mode - Same as above with different transmitter and receiver settings.
- Dual Mode - Duplex conference between astronaut one, astronaut two, and space vehicle/earth; simultaneous telemetry for each astronaut.

The normal mode during EVA is the dual mode.

Transmission of both voice and telemetry data from the second astronaut is accomplished by the EVCS. Astronaut one receives astronaut two's voice and telemetry data and, along with his own, transmits this signal to the Lunar Module (LM). Earth, via the LM, then communicates with either or both astronauts through their receivers. In the event the EVCS dual mode fails, or if only a one man EVA is desired, the primary and secondary modes will act as contingency modes of operation.

The EVCS has provisions for connection to transducers, microphone, electrocardiograph, antenna, calibration receptacle, mode selector switch, volume control, and power input.

The following list delineates the Portable Life Support System (PLSS) and Pressure Garment Assembly (PGA) instrumentation signals, which are telemetered to the Manned Space Flight Network:

- PGA pressure transducer
- LCG inlet temperature transducer
- Battery current transducer
- EKG
- O_2 bottle pressure transducer
- Feedwater pressure transducer
- LCG differential temperature transducer
- Sublimator outlet gas temperature transducer
- Battery voltage
- CO_2 sensor

The telemetry portion of the EVCS has 30 channels:

- 26 telemetry
- 2 calibration
- 2 synchronized with ground station on earth

All 26 telemetry channels are not needed for this application, but they do enable the unit to be used for future PLSS requirements.

The Communications Carrier Assembly (CCA) to which the EVCS interfaces consists of a head fitted assembly with redundant earphones and microphones. The telemetry portion of the CCA is supported by the Constant Wear Garment for transmission of biomedical data by providing pass-throughs for the electrical harness, attachment provisions for the electrical harness, and a bio-belt (parts of the bioinstrumentation system) (ref. 3.13).

3.7.3 Skylab

The Skylab Communications System is comprised of the following subsystems (ref. 3.22):

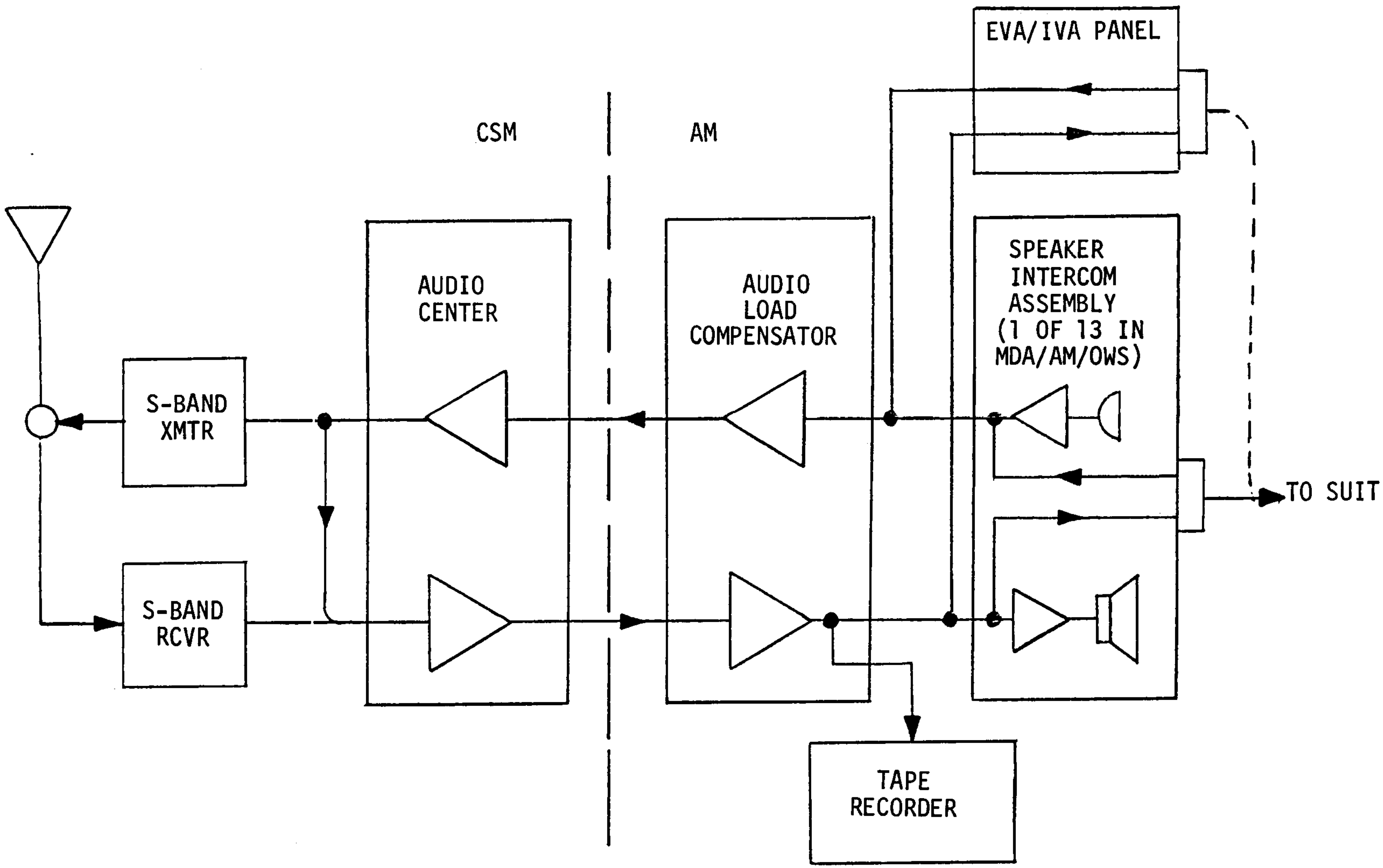
- Audio
  - Voice
  - Caution and Warning (C&W) Tone
- Very High Frequency (VHF) Ranging
- Radio Frequency
  - Telemetry (TM) Downlink
  - Digital Command System (DCS) Uplink
- Teleprinting
- Television

The following is a brief discussion of the current Skylab Communications and Telemetry System components which are used during EVA.

The Audio System, in conjunction with the Apollo Voice Communications System, provides communications between the three Skylab crewmen and the Manned Space Flight Network (MSFN). All real-time voice transmissions to the MSFN from the orbiting assembly are relayed by the CSM via S-Band. Voice, recorded on the Instrumentation System tape recorders, is transmitted to the MSFN in delayed time by means of the Airlock Telemetry Transmission System. The Audio System consists of thirteen Speaker Intercom Assemblies (SIA), an IVA Panel, two EVA/IVA Panels, two Audio Load Compensators including Tape Recorders, and three Crewman Communication Umbilicals, not counting the three Life Support Umbilicals (LSU) (ref. 3.32). Figure 3-50 shows a block diagram of the Cluster Audio System (ref. 3.32). Figure 3-51 depicts the EVA/IVA Communication Interface.

Each crewman will be supplied with two isolated microphone-amplifier assemblies (one for redundancy). A hardline two-way communications is used in conjunction with the CM or AM Systems. Figure 3-52 shows the hardwire SIA/CCU Interface. Hardline communications is accomplished using either of two crew umbilicals associated with data transfer and communications. Table 3-26 (p. 3-121) describes those umbilicals and their functions. The EVA/IVA umbilicals' interface with the EVA Control Panel is illustrated in Figure 3-53. Figure 3-54 shows the Speaker Intercom Assembly (ref. 3-31), and Figure 3-55 shows the SIA and EVA/IVA Panel locations in the Skylab Orbital Assembly.

The Time Reference System (TRS), in conjunction with the Digital Command System(DCS) Receiver/Decoders, provides time correlation to the Pulse Code Modulation Data System, automatic reset of certain DCS commands, automatic control of the redundant DCS Receiver/Decoders, Greenwich Mean Time (GMT)



FIGLRE 3-50: Skylab Cluster Audio System (One of Two Channels Shown)

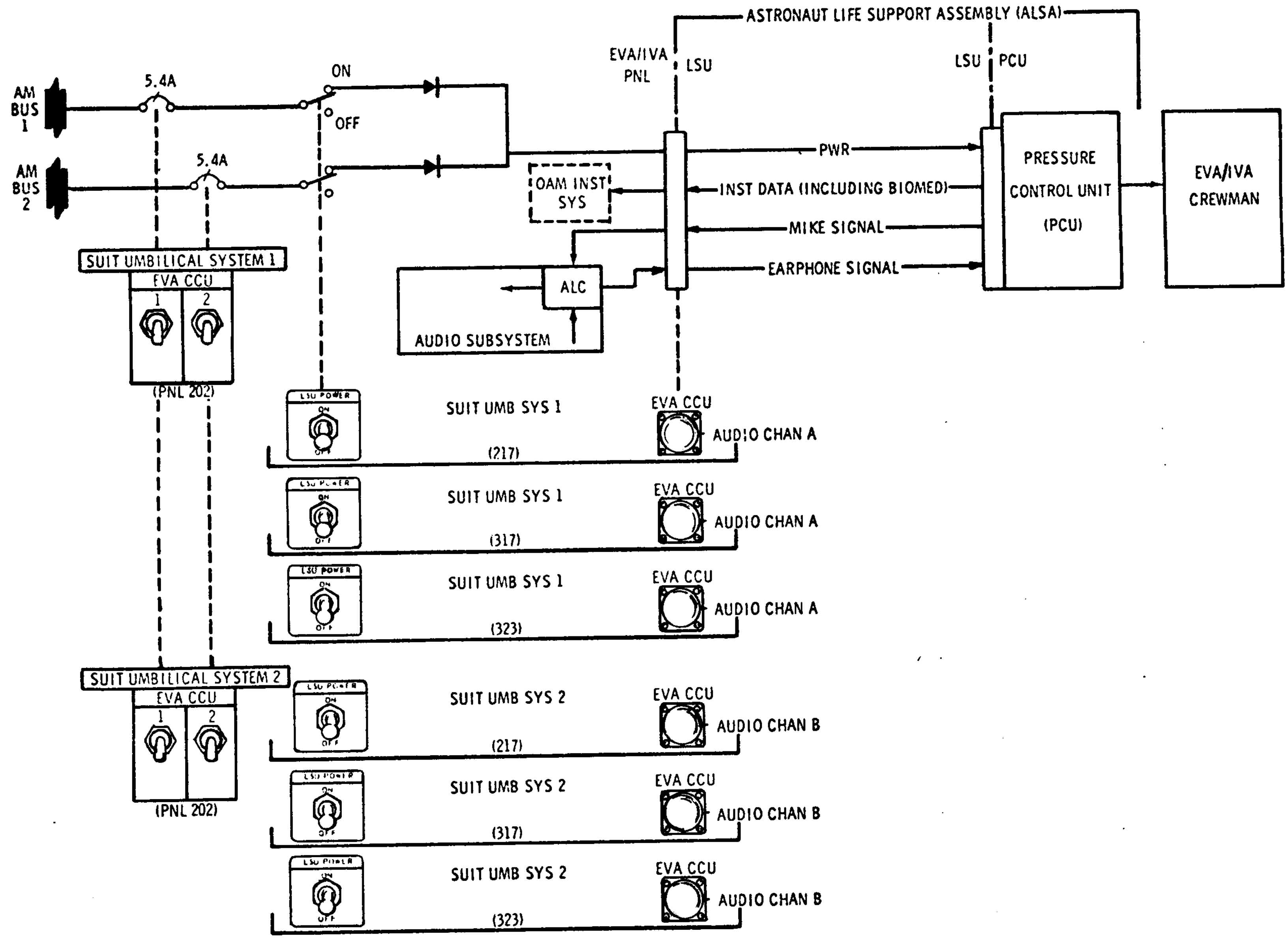


FIGURE 3-51: Skylab EVA/IVA Communication Interfaces

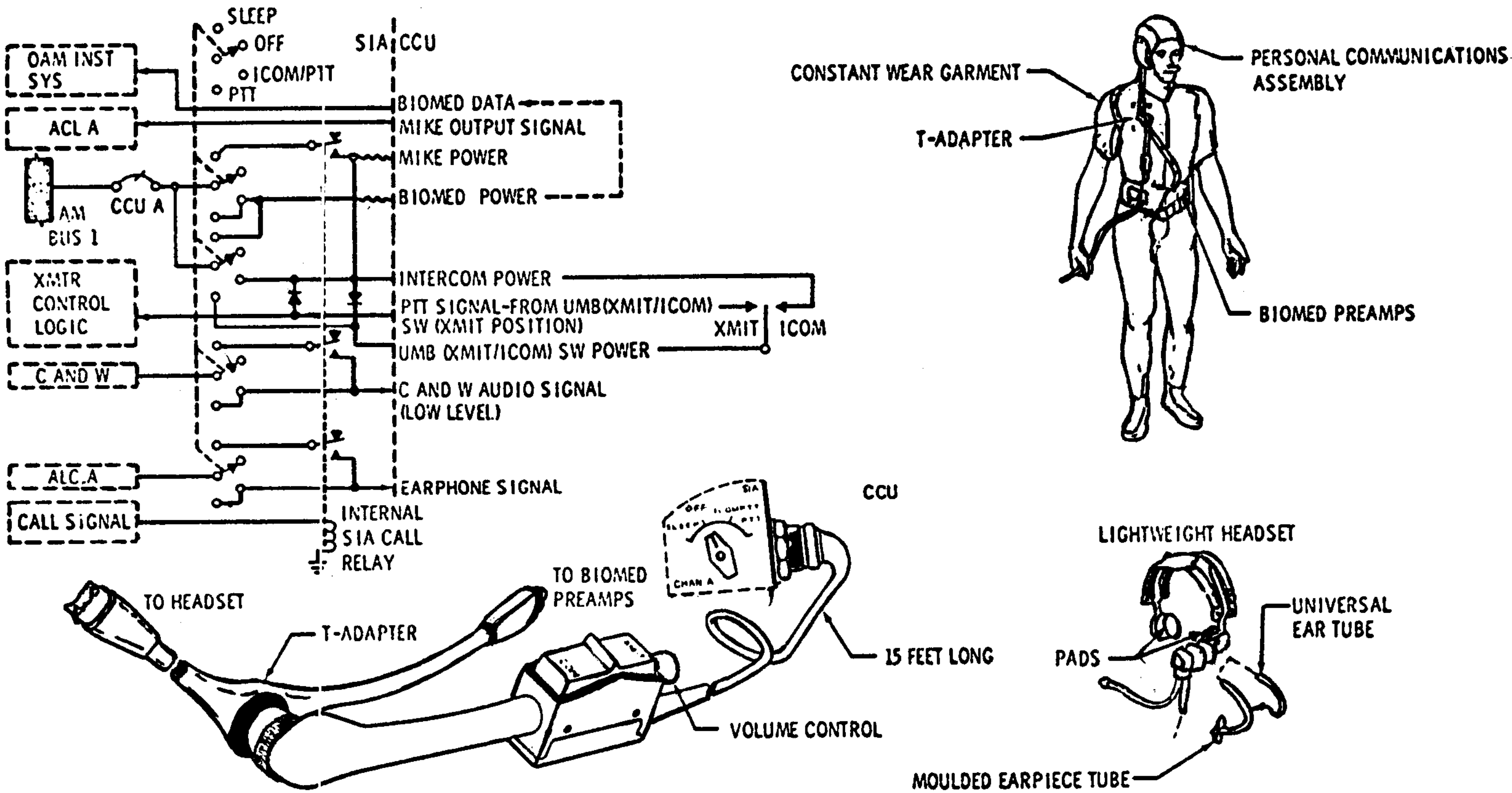


FIGURE 3-52: SIA/CCU Interface

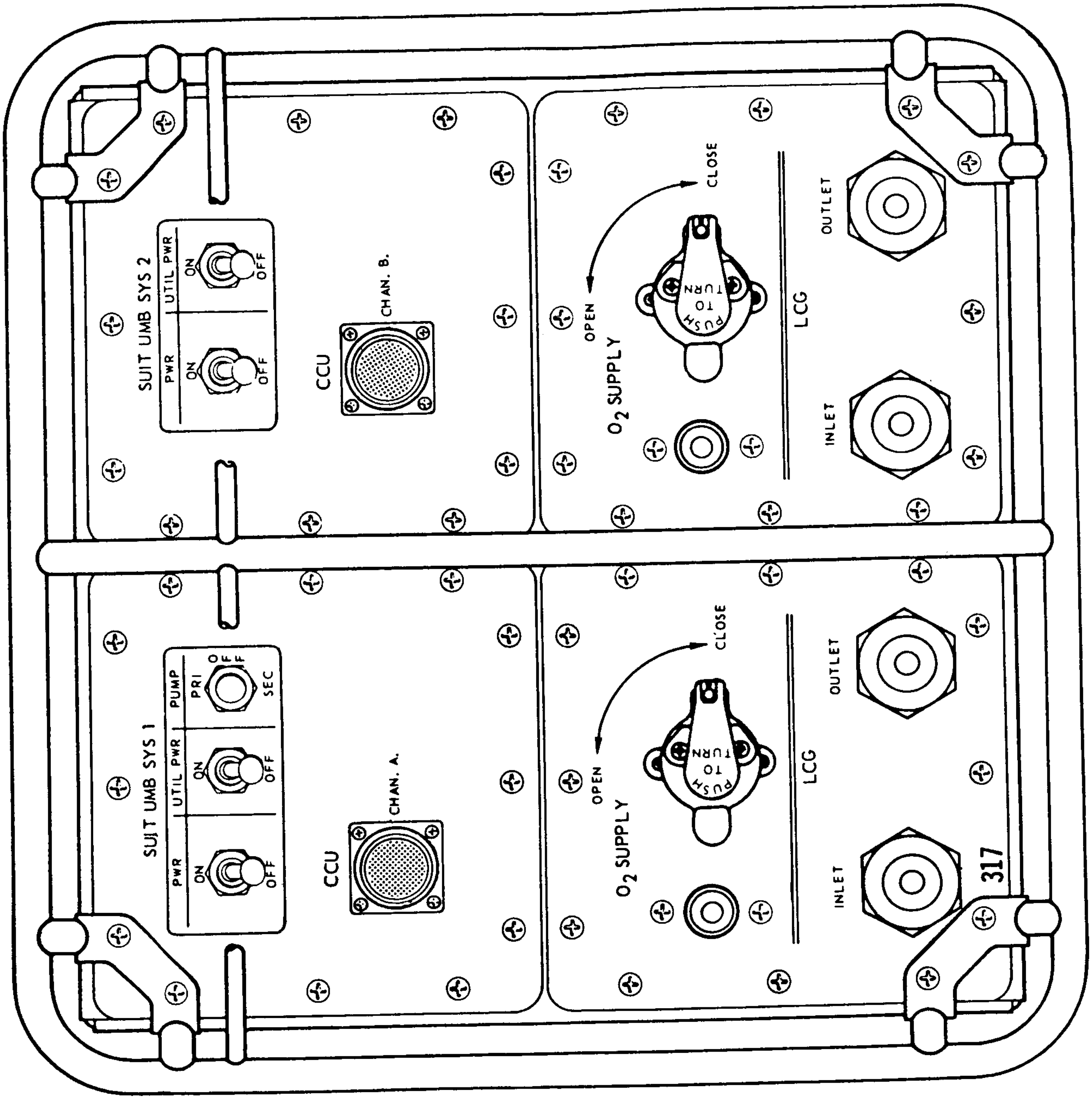
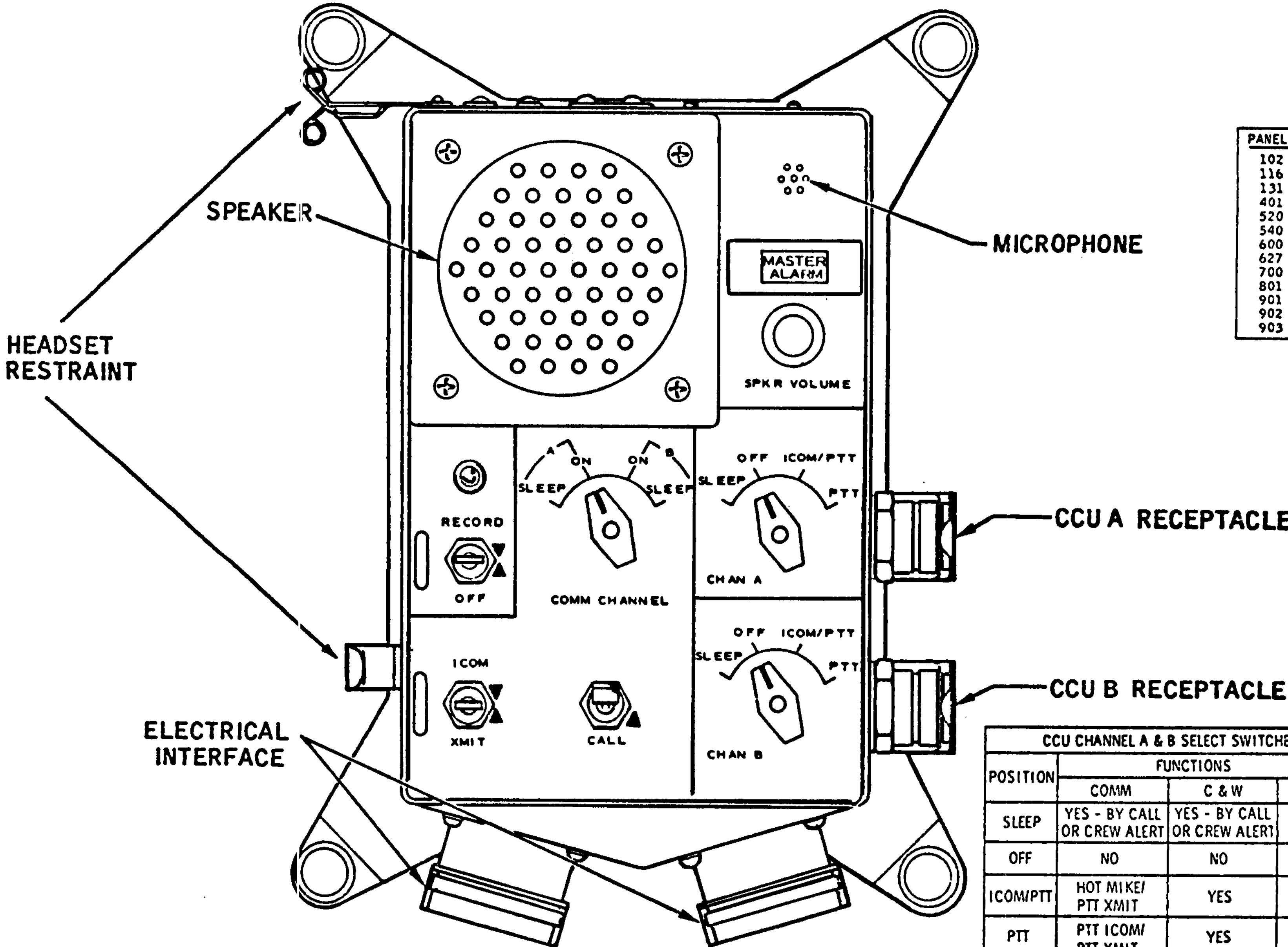


FIGURE 3-53: Skylab EVA No. 1 Control Panel



PANELS
102
116
131
401
520
540
600
627
700
801
901
902
903

CCU CHANNEL A & B SELECT SWITCHES			
POSITION	FUNCTIONS		
	COMM	C & W	BIOMED
SLEEP	YES - BY CALL OR CREW ALERT	YES - BY CALL OR CREW ALERT	YES
OFF	NO	NO	NO
ICOM/PTT	HOT MIKE/ PTT XMIT	YES	YES
PTT	PTT ICOM/ PTT XMIT	YES	YES

FIGURE 3-54: Skylab Speaker Intercom Assembly (SIA)

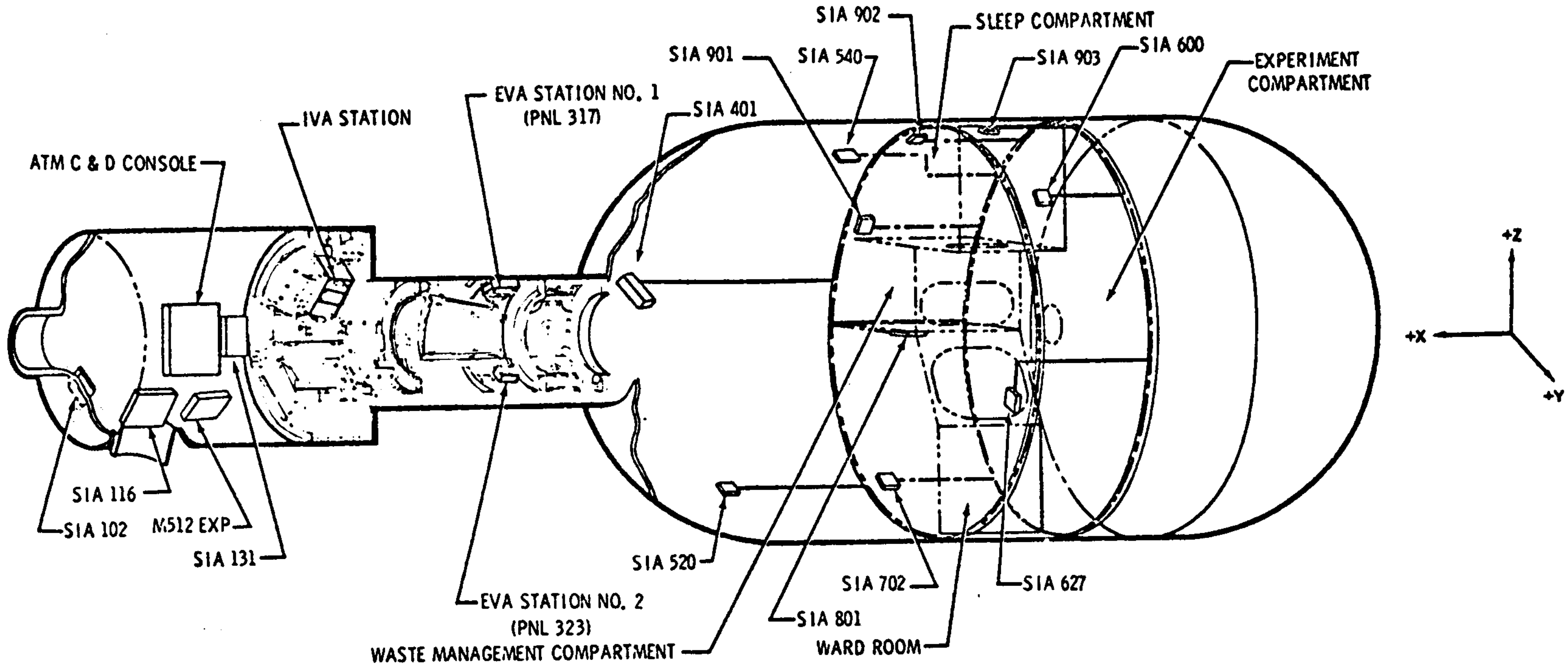


FIGURE 3-55: Skylab SIA and EVA/IVA Panel Locations

TABLE 3-26: Crew Umbilicals

Type	Quantity	Length	Functions	Comments
1. EVA/IVA (GFE)	(3)	60 Ft.	Tether O_2, H_2O Communications Biomedical Utility Power	Interfaces with the Pressure Control Unit (PCU) & Press. Suit connects to receptacle in the EVA lock compartment and in the STS. No emergency and warning tone for EVA.
2. Personnel Comm/ Biomedical	(3)	15 Ft.	Communications Biomedical data Emergency & Warning	Connects to any Airlock/MDA/OWS Speaker Intercom

data to the Earth Resources Experiment Package, and on-board displays of GMT and elapsed event time. The TRS consists of two Electronic Timers for redundancy, two Time Correlation Buffers for redundancy, two Digital Display Units, and one Digital Clock (ref. 3.22).

The Airlock VHF Ranging System utilizes the LM transponder equipment to facilitate the rendezvous of Command Modules (SL-2, -3, and -4) with the Saturn Workshop (SL-1). The Airlock equipment consists of a VHF Transceiver Assembly, a Ranging Tone Transfer Assembly, and a VHF Ranging Antenna. Audio tones of precise frequency are generated in the Command Module and Transmitted to the Airlock. The tones are received, reconstructed, and retransmitted to the CM by the Airlock transponder equipment. Accurately measuring the time delay from the transmission of a tone until the same tone is received back in the CM gives the range between the two vehicles. The ranging signals generated in the CM are three audio tones, 3.95 kHz, 247 Hz, and 31.6 kHz (ref. 3.22).

The Telemetry Transmitters provide the means for transmitting data to the MSFN using four telemetry transmitters consisting of three 10-watt units and one 2-watt unit. The 2-watt transmitter will be used during the launch phase of SL-1 and will serve as a backup transmitter for one of the 10-watt transmitters during orbit phases of the mission. Switching, controlled either manually or by DCS ground command, permits the transmission of either real-time or tape recorded delayed time data and voice information.

The Airlock Antenna System consists of a modified Gemini Quadriplexer, two Gemini UHF Whip Antennas, four RF Coaxial Switches, two Antenna Booms, two Discone Antennas, and a helical VHF Ranging Antenna (ref. 2.22).

The Airlock Caution and Warning System provides both visual and audible indications of adbormal operation of specific functions in the Airlock, OWS, MDA, ATM and CM. Faults originating in the CM close a relay which energizes a light on the Structural Transition Section advisory panel and also activates the AM warning tone. Faults occurring in the OWS, MDA, ATM and AM energize the appropriate lights on the advisory panel and activate the proper audio tones (i.e., Caution, Warning, or Emergency). The Airlock Caution and Warning System consists of a Caution and Warning Unit, two Klaxons (one in the AM tunnel and one in the OWS), caution/warning, sensors, emergency sensors and a fault advisory panel to indicate where the fault originated (ref. 3.22).

The Airlock Digital Command System provides the Manned Space Flight Network with real-time command capabilities for the OWS, MDA, docked CSM, and Airlock during all phases of the mission for control of experiments, antennas, and system functions necessary to achieve mission objectives. The DCS consists of two Digital Command Receiver/Decoders for redundancy, four Relay Modules, and a Command Relay Driver Unit. The redundant Digital Command Receiver/Decoders are necessary to ensure continuous command capability for the entire Airlock mission (ref. 3.22).

The Teleprinter System, in conjunction with the DCS Receiver/Decoders, provides the capability for printing detailed data transmitted from the MSFN. The teleprinter system consists of a teleprinter and an Interface Electronics Unit (IEU). The IEU is used to interface the teleprinter with the DCS Receiver/Decoders (ref. 3.22). Figure 56 shows the Skylab EVA Communications Systems location within the Airlock Module.

3.8 DATA/INFORMATION MANAGEMENT

3.8.1 Introduction

Astronauts, while working in the hostile space environment, will develop certain physiological and performance characteristics which differ from those on earth due to their weightlessness in the space environment, the restrictions of the pressurized suits, the workloads imposed on them, and the general EVA environment.

Certain physiological parameters and performance characteristics should be measured to determine what differences exist and to monitor the condition of the crewmen (ref. 3.32).

3.8.2 Monitoring Techniques/Systems

Biomedical data have been provided to demonstrate man's ability to survive and perform intravehicular and extravehicular tasks. The Apollo and early Apollo Applications Programs increased the need for medical information. Factors having significant impact on medical information requirements included the number of crewmen, mission duration, and flight complexity.

COMMUNICATIONS SYSTEMS

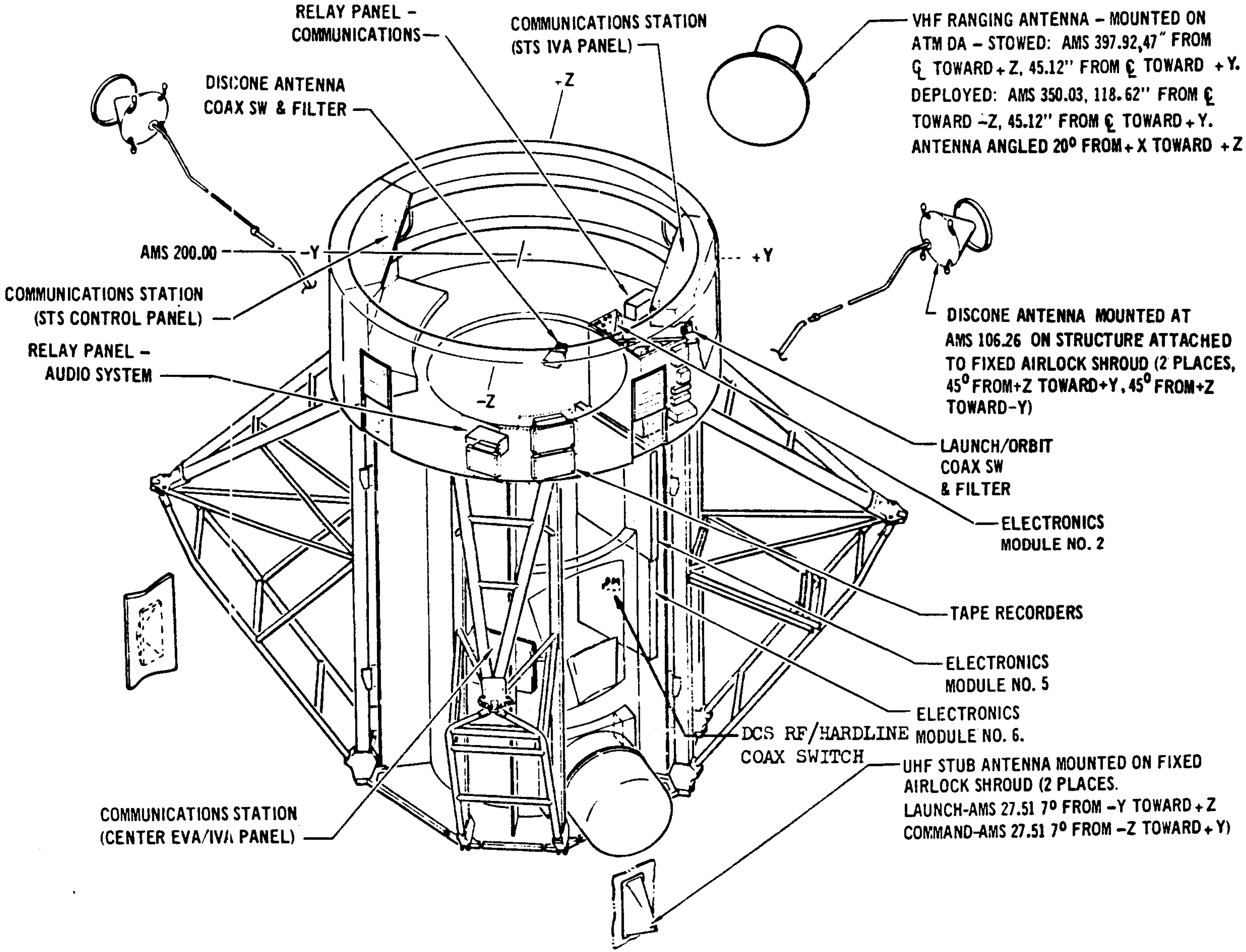


FIGURE 3-56: Skylab EVA Communications Systems (Airlock Shown)

Because of a limited number of telemetry channels, only those physiological variables that are considered necessary for determination of the well-being of the flight crew are monitored. In the Mercury and Gemini flights, real-time measurements were presented in analog with no analog-digital conversion or preprocessing. A tape recorder was used to record the measurements in analog form. In this way, more comprehensive physiological data for an in-depth postflight analysis could be provided.

Table 3-27 shows the types of data obtained through biomedical monitoring during the Mercury, Gemini and Apollo missions, along with the means for obtaining such data.

TABLE 3-27: Types of Biomedical Monitoring from Spacecraft

Factor Monitored	Mercury (1-man Crew)	Gemini (2-man Crew)	Apollo (3-man Crew)
ECG	Bipolar electrodes	A&S[a], 320[b]	A&S[a], 200 sps[b]
Respiration	Thermistor and impedance pneumograph	Impedance method, 40 sps; axillary ECG electrode used as sensor	Impedance-pneumograph, 40 sps
Blood Pressure	Arm cuff and microphone	Manual, squeeze-bulb, brachialocclusive system	Mechanical, squeeze-bulb, ad libitum
Body Temp.	Rectal probe and oral sensor	Oral thermistor probe; 1.2 sps; intermittent	Oral, mechanical, ad libitum
PKG[c]	None	Routed with EEG to tape recorder (experiments data)	200 sps

[a]Axial and sternal. [c]Phonocardiographic.
[b]Samples per second.

Figure 3-57 illustrates a typical method by which physiological data and other information is transmitted from the astronaut and received at appropriate data centers. The chart represents a typical Gemini mission.

The most advanced biomedical monitoring system is the Skylab Operational Bioinstrumentation System (OBS). This system is an individually adjusted system which monitors the physiological functions of each crewman during specified periods of the mission. The functions to be monitored during EVA are (ref. 3.33):

- Electrical Activity of the Heart
- Heart Rate
- Respiration Rate
- Body Temperature

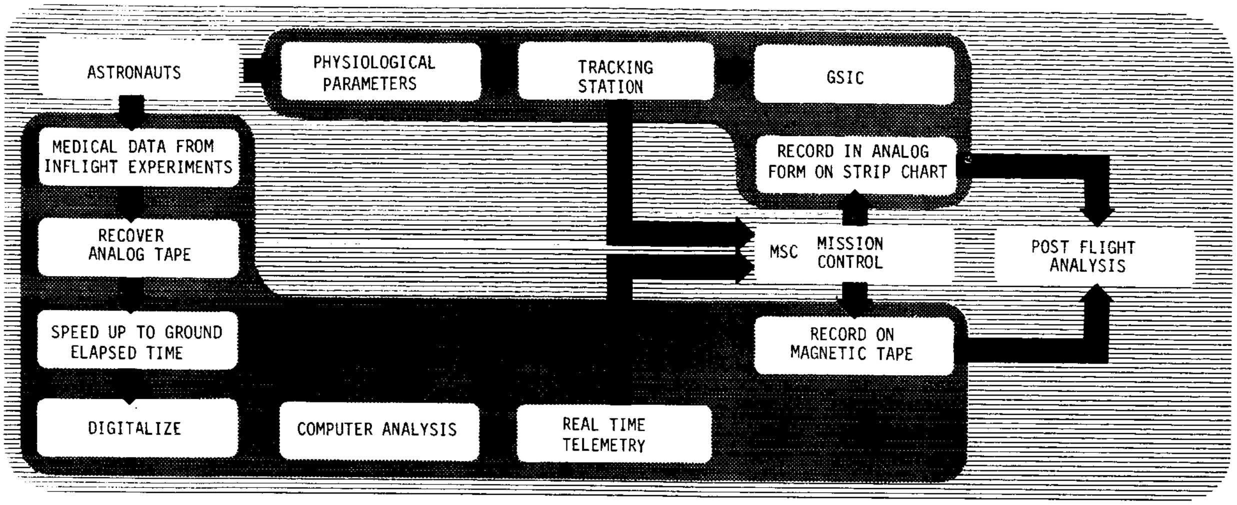


FIGURE 3-57: Typical Gemini Data Transmission

Figure 3-58 shows the usefulness of telemetered inflight data obtained from the OBS. The data, once received by the ground, will be compared with pre-flight baseline data. Comparison of the data will provide for: 1) evaluation of each crewman's health, 2) diagnosis of illness or injury, 3) assessment of physiological aspects of crewman safety, and 4) a basis for study of medical aspects of manned spaceflight.

The OBS monitoring of crewman well-being will be performed during launch and ascent, specified orbital operations, IVA in suited mode, EVA, reentry, and upon command from ground medical monitors. Any two crewmen can be monitored simultaneously in the OWS; all three can be monitored in the CM.

Figures 3-59 and 3-60 show the OBS components that are worn by the crewman. The OBS block diagram is shown in Figure 3-61.

The Skylab OBS consists of the following components:

- Electrocardiograph Signal Conditioner (ECG)
- Impedance Pneumograph Signal Conditioner (ZPN)
- Cardiotachometer Signal Conditioner (CTM)
- Body Temperature Measuring System (TEM)
- Subject Identification Module (SIM)

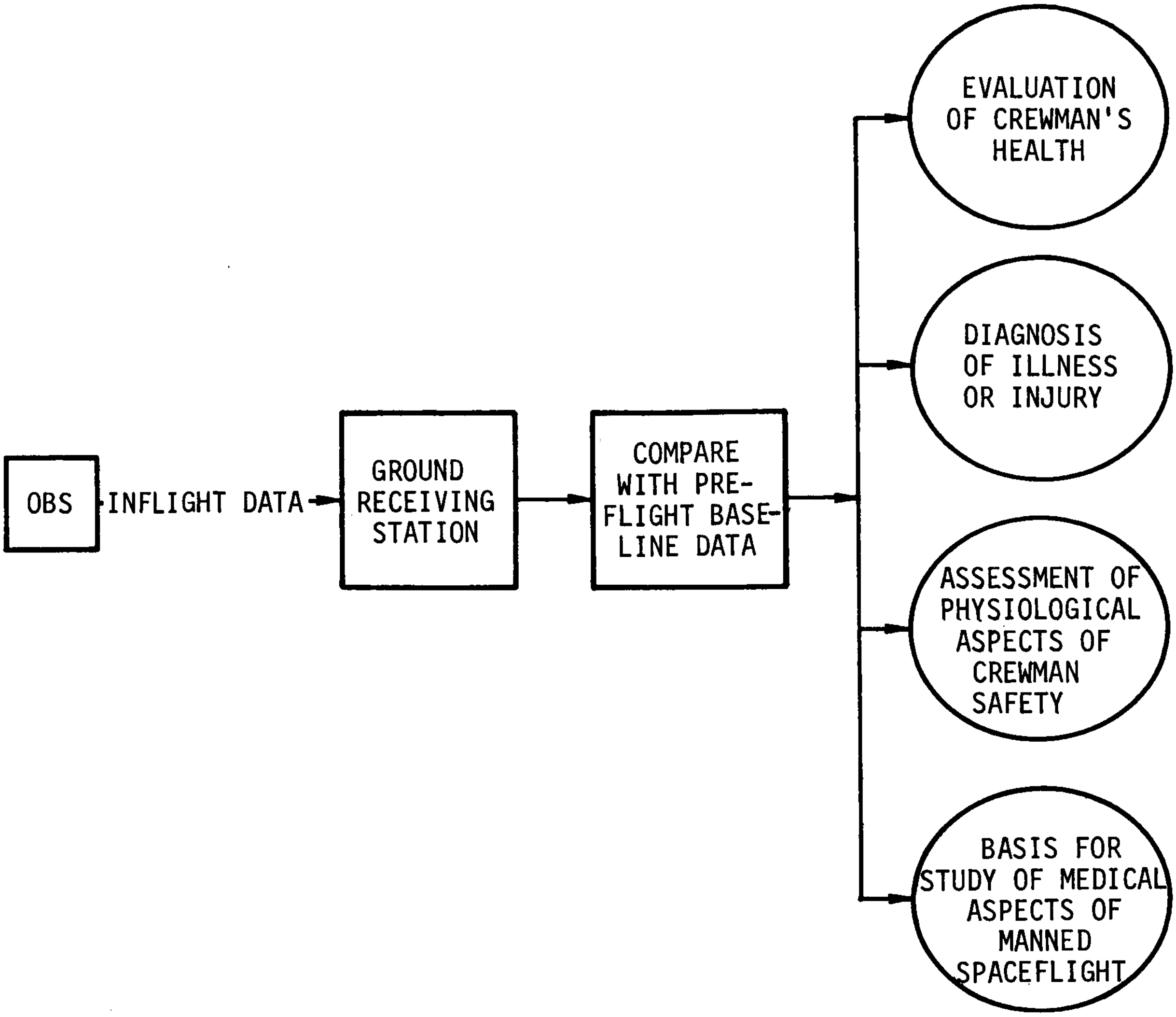


FIGURE 3-58: Usefulness of Inflight Data Telemetry

- DC-to-DC Converter (DCC)
- Electrical Harness Assembly (EHA)
- Bio-Belt
- Sternal Electrode Harness
- Axillary Electrode Harness

In addition to biomedical data, suit status parameters are also transmitted to the ground for monitoring during extravehicular activities. These include the parameters outlined below:

The Extravehicular Mobility Unit (EMU) transmits the following telemetry data through the CSM and OA telemetry systems:

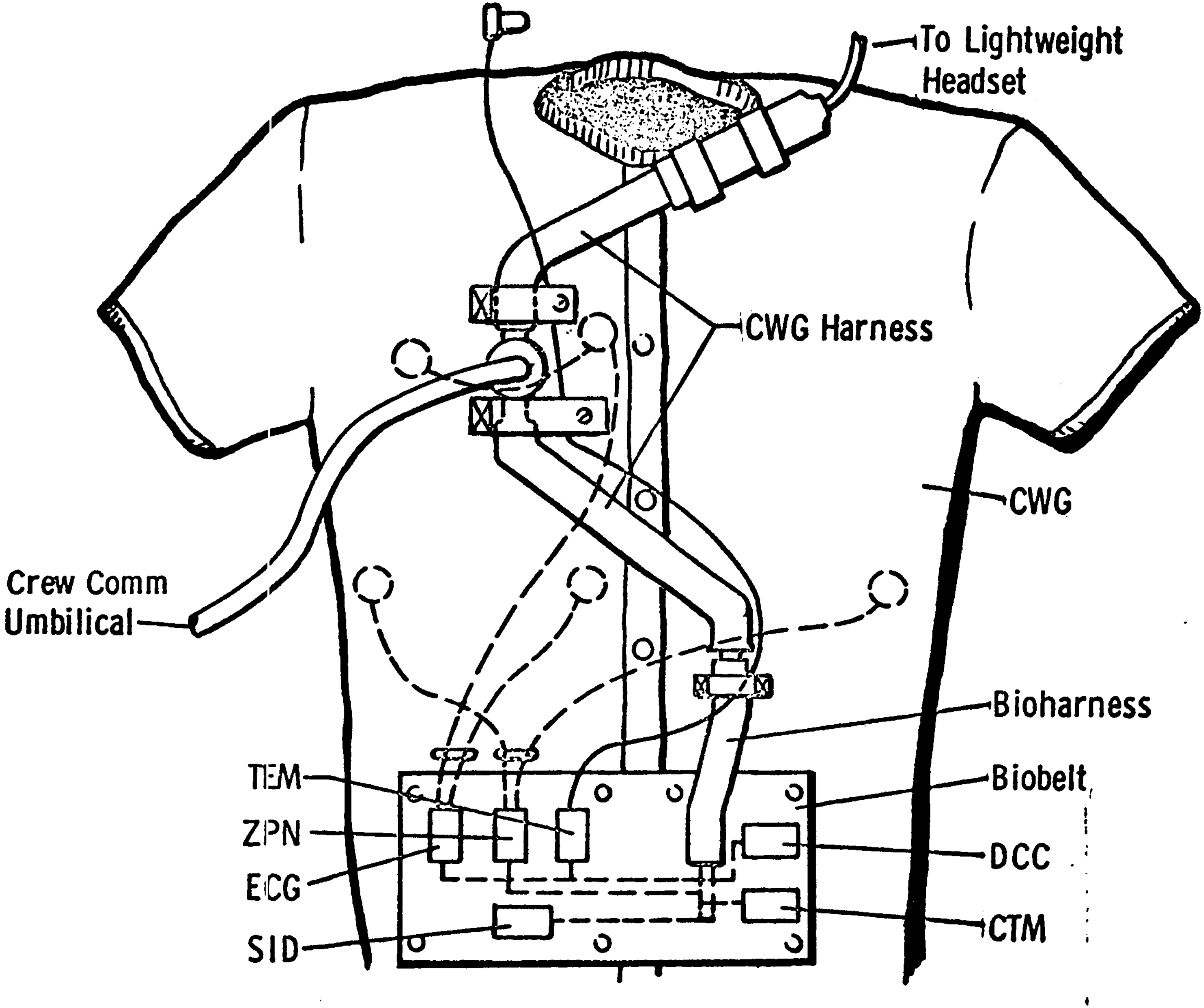


FIGURE 3-59: OBS Unsuited Mode (Skylab)

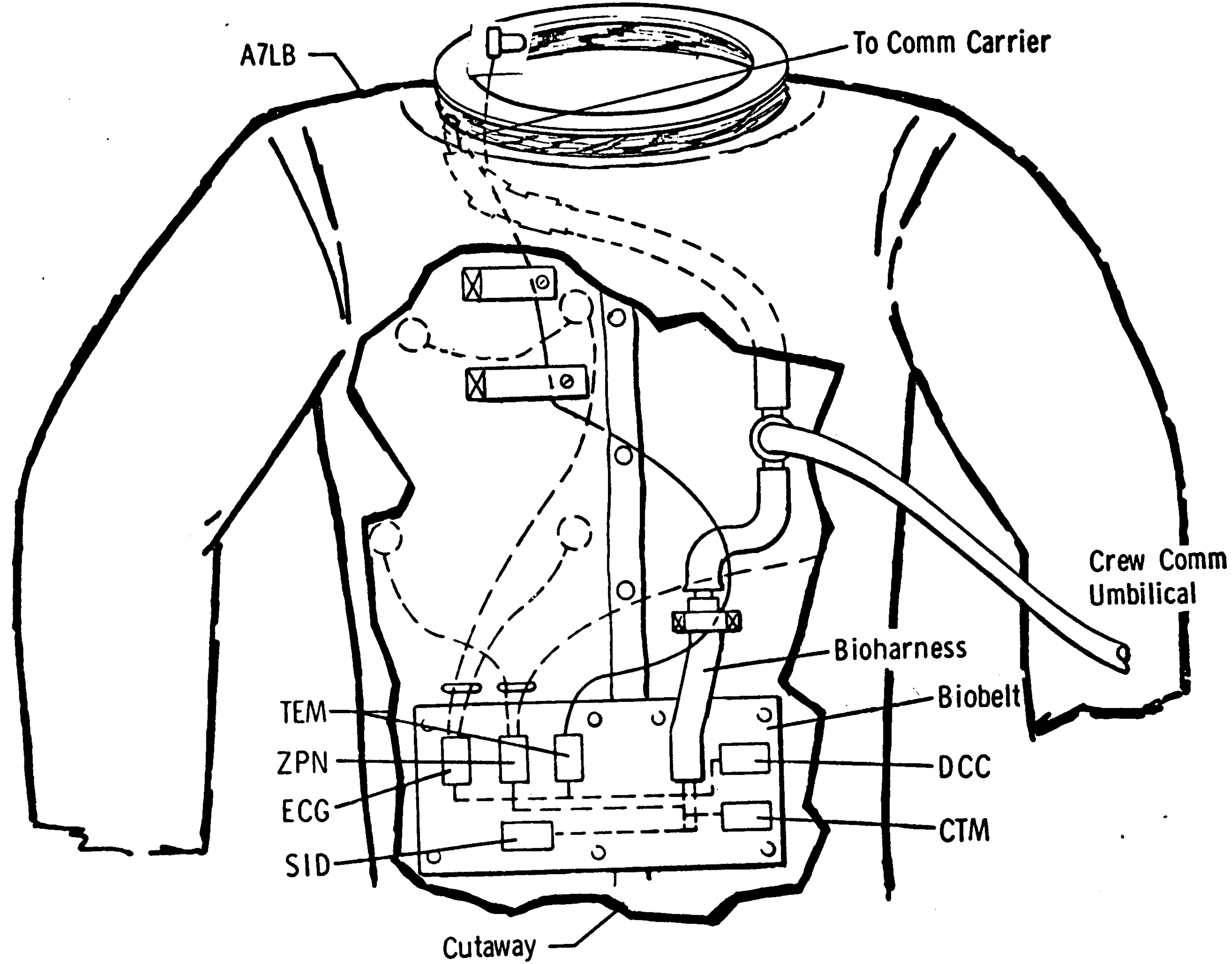


FIGURE 3-60: OBS Suited Mode (Skylab)

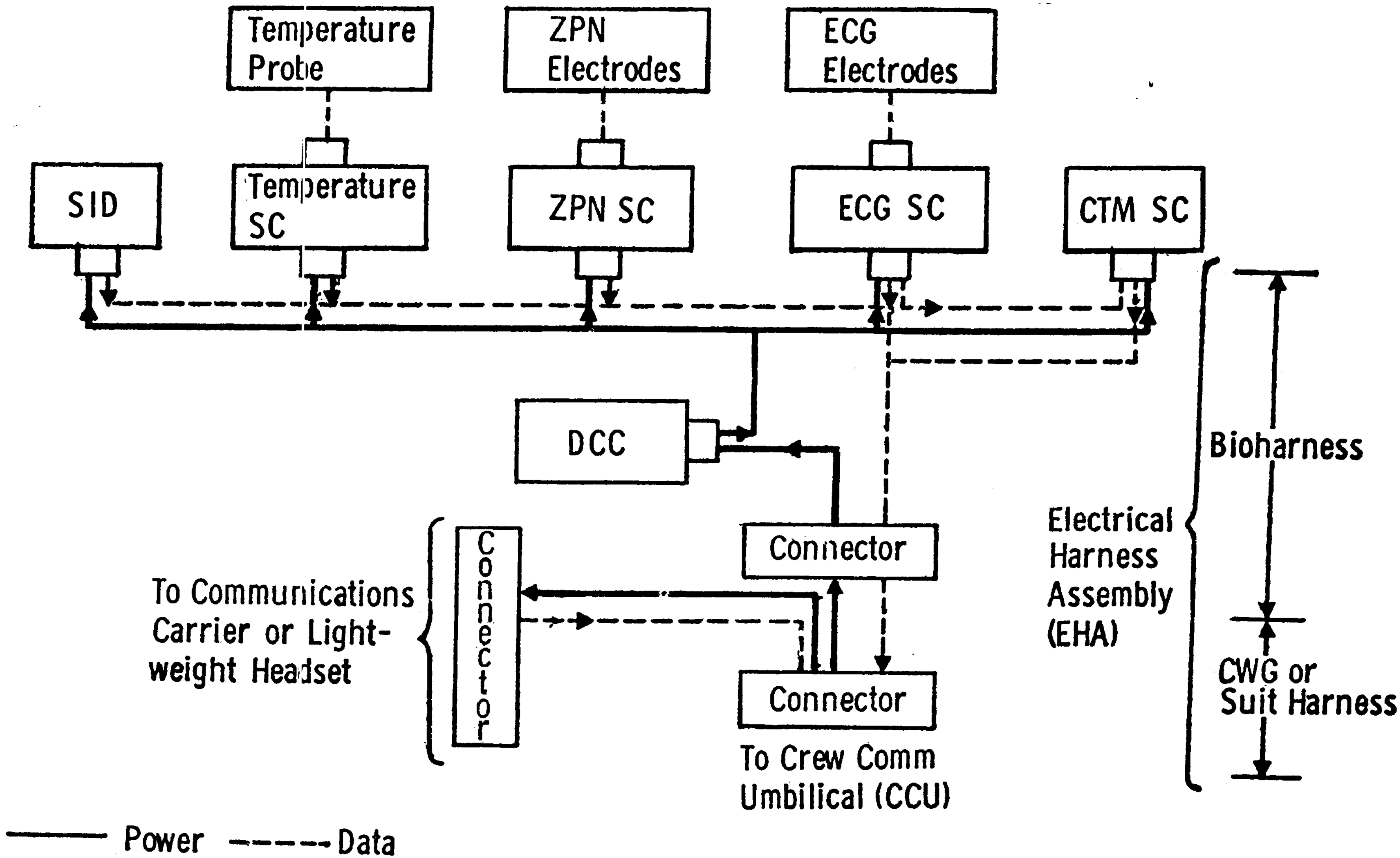


FIGURE 3-61: OBS System Block Diagram

- Environmental Parameters
  - Pressure
  - O_2 inlet temperature
  - O_2 outlet temperature
- Performance parameters
  - supply H_2O temperature
  - return H_2O temperature
- Physiological parameters - generated by the Bioinstrumentation System
  - EKG activity
  - respiration rate
  - heart rate
  - body temperature
  - subject identification

3.8.3 Instrumentation System

The purpose of the Skylab MDA/AM/OWS Instrumentation System is to acquire all real and delayed time instrumentation required for mission control, subsystem status, biomedical monitoring and experiments support. It also provides the capability for recording voice with subsequent delayed time transmission to the MSFN. The Instrumentation System is active during Crewman Extravehicular Activity.

The following is a brief description of the electronic equipment needed for data handling and transmission during Skylab Extravehicular Activity. Performance data, along with additional systems information, is given in Table 3-28 (ref. 3.34).

3.8.3.1 PCM Programmer

The PCM programmer operates as a self-contained data handling unit, since it provides internally the functions of:

- data multiplexing
- analog-to-digital data conversion
- digital data multiplexing
- central synchronized timing
- sampling functions to support the multiplexing functions performed by the internal multiplexers
- other functions to produce a real-time nonreturn to zero PCM pulse train and a return to zero subframe signal for recording

TABLE 3-28: Data Handling Equipment During EVA

DATA MANAGEMENT SYSTEM	PHYSICAL CHARACTERISTICS	PERFORMANCE CHARACTERISTICS
PCM Interface Box	Size: 10" x 11" x 14.5" Weight: 62 lbs.	• Power: 15 watts @ 24 VDC regulated. • Receives power from DC to DC converter and develops voltage for up to 34 remote multiplexers. • Provides 24 bit parallel time word and 3 subframe outputs for recording. • Provides timing pulses for programmer. • Direct input capability for sampling the following direct input HL signals: - 18 channels @ 10 sps - 5 channels @ 320 sps - 8 channels @ 80 sps - 1 channel @ 40 sps - 5 channels @ 20 sps
PCM Programmer	Size: 11" x 12" x (2.3" - 4.6") Weight: 20.2 lbs.	• Power: 6 watts @ 24 VDC regulated. • Generates central timing for the system. • Provides: - 2.4 second reset pulse - 160 bps timing pulse - 12.8 KBPS word rate pulse - bit (2,3) and bit (5, 6, 7) timing pulses - 5.12 KB clock - RZ timing pulse - C3 shift pulses - 51.2 KBPS PCM output - TRS data and clock to the Interface Box to create the AM PCM format. • Provides channel gating for 3 low level multiplexers. • Contains direct input capability for: - 32 HL channels @ 1.25 sps - 6 HL channels @ 10 sps - 6 LL channels @ 160 sps - 9 LL channels @ 80 sps - 40 bilevel channels • Produces command functions for transfer of the 24 bit time words from the Time Reference System.

TABLE 3-28: Data Handling Equipment During EVA (Cont'd.)

DATA MANAGEMENT SYSTEM	PHYSICAL CHARACTERISTICS	PERFORMANCE CHARACTERISTICS
PCM cont'd.		• Produces a 51.2 KBPS PCM hardline output, a 51.2 KBPS filtered NRZ output to the transmitter, and an RZ and tape recorder clock output to the AM tape recorders.
Tape Recorder/ Reproducer	Size: 10" x 10" x 4.31" Weight: 15.0 lbs.	• Power: 15.5 watts @ DC regulated. • At dump command, it plays back the stored data in reverse order to which it was recorded. • Max. record time - 240 minutes. • Has "end-of-tape" switch that automatically prevents the tape from winding completely off the supply reel. • Has "start-of-tape" switch that provides a similar function as the "end-of-tape" switch; functions during playback mode. • Has fast forward mode which permits operation of the machine in the record direction at the fast playback speed to permit re-dump of previously dumped data.
Transmitter (4 ea.)		• Frequency modulated in the 225 to 206 MHz band and operated under duty cycles ranging from 1 to 100%. • Power output: 10 watts for the 230.4 MHz, 246.3 MHz and 235.0 MHz transmitters at supply voltage from 30.5 to 18.0 VDC. • A 230.4 MHz 2 watt transmitter is provided to supply the RF unit during launch.

3.8.3.2 PCM Interface Box

The PCM Interface Box provides a redundant means for supplying power and timing for:

- remote multiplexers
- sampling HL data directly
- switching data from remote multiplexers into the programmer

3.8.3.3 Tape Recorder/Reproducer

The Tape Recorder/Reproducer provides continuous mission coverage in delayed time for:

- systems data
- experiment data
- crewman voice

The tape recorder receives data from the programmer and stores it on Track A while Track B is capable of recording astronaut voice. Maximum recording time for the tape recorder is four hours; however, by operating the three units sequentially, twelve hours of continuous recording is possible. Upon receipt of a playback command from the ground station, the recorder rewinds the tape onto the original reel at 22 times the recording speed, with the recorded data output of Track A directed to the transmitter in NRZS format and the voice recording on Track B directed to a voice transmitter. Immediately upon removal of the playback command, the recorder switches from playback mode to record mode.

3.8.3.4 Transmitters

The telemetry transmitters provide an RF link from the spacecraft to ground communication facilities.

Figure 3-62 is a functional schematic of the Instrumentation System and its interfaces. The Transducers are the source of biomedical as well as other data in the system. Figure 3-63 is a functional block diagram showing the Biomedical and Audio Subsystems Interface Block Diagram.

Valuable information has been obtained through voice monitoring of all flights. A major data gathering addition in the Apollo program is television transmission, which enables the visual monitoring of the crew. Many environmental parameters, such as suit pressure and temperature, are now monitored. The sampling rates are generally 0.5 - 1.2 sps., and the data are transmitted with pulse-code modulation (PCM).

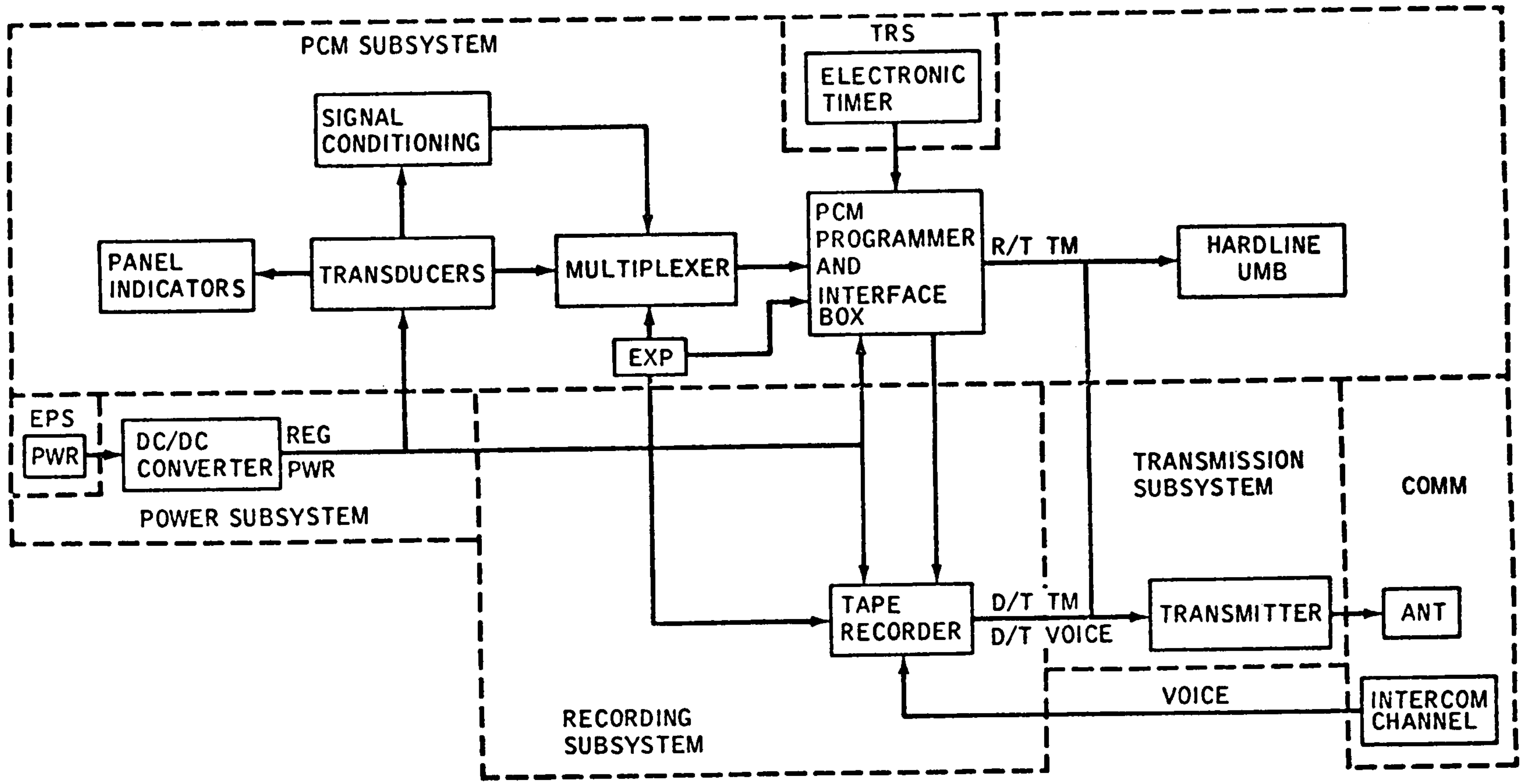


FIGURE 3-62: Skylab MDA/AM/OWS Instrumentation System/Functional Schematic

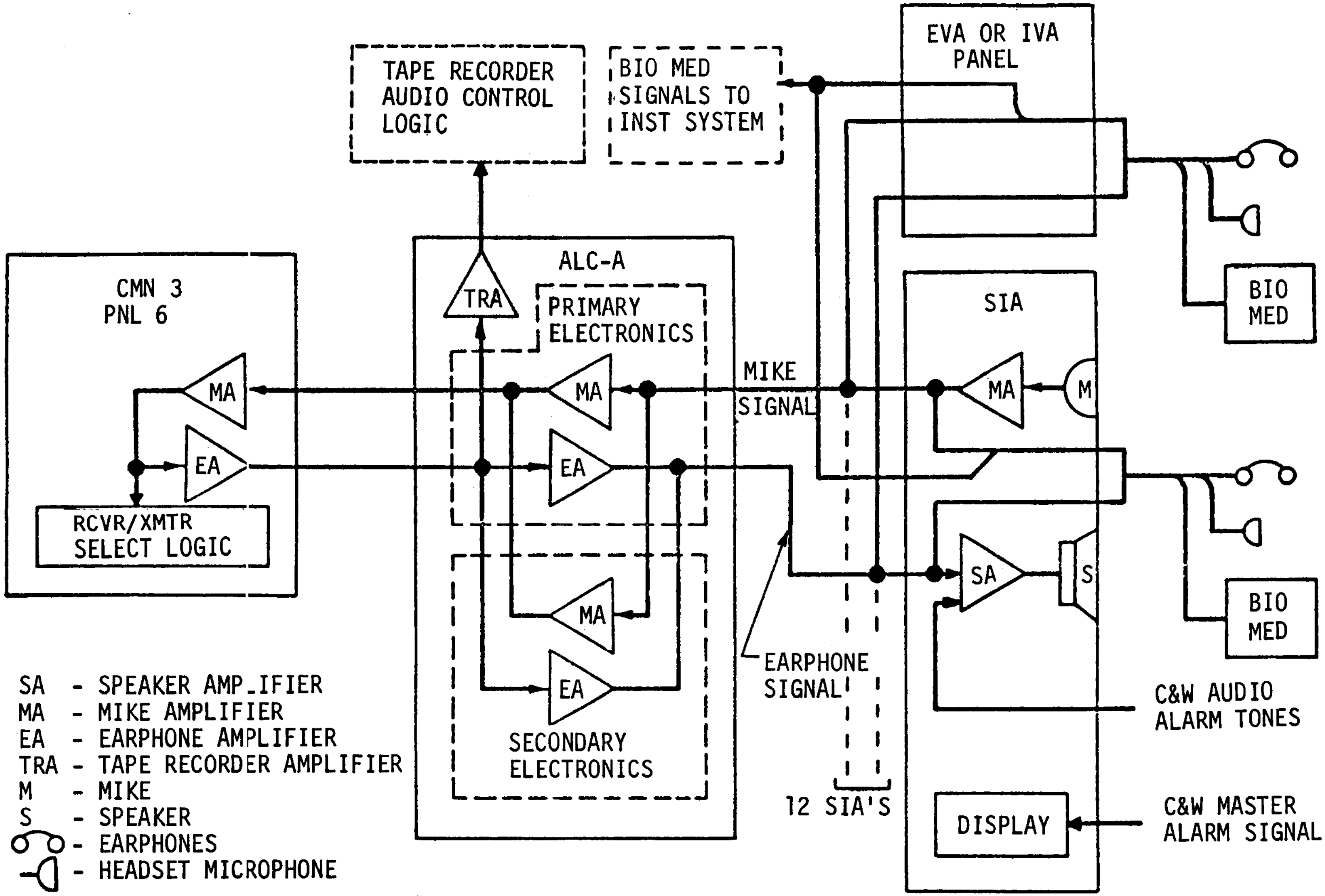


FIGURE 3-63: Skylab Biomedical and Audio Subsystems Interface Block Diagram (Channel A Shown)

3.9 EVA TOOLS

3.9.1 Introduction

The use of tools during orbital EVA operations has been very limited on previous spaceflights. The type of orbital EVA functions required on the Gemini and Apollo missions generally excluded the need for tools. Gemini IX-A and XII EVA operations did, however, include an exercise to evaluate the following hand tools.

TOOL	OPERATION
Wrench	Tighten 1/2 and 1/4 in. fixed bolts and remove/replace Saturn bolt.
Torque Wrench	Perform torquing operations of fixed bolts.
Cutting	Cut two strands of cable.

No problems were encountered during the evaluations where the proper restraint systems were provided. The orbital EVA operations on Apollo 9, 15 and 16 required no tools.

Numerous research and technology programs were conducted between early 1963 and 1969 to develop and evaluate various power and hand tools for zero and reduced gravity applications, particularly for use in an extravehicular (EV) environment. Many special purpose tools were developed to reduce operator energy expenditure, maintain operator and equipment orientation, and provide rapid-actuating multiple-function tools. Concurrent with many of the special tool development efforts, resulting from the early Gemini EVA missions, was an increased emphasis on the development of improved crewman restraint systems, space suits with increased mobility, life support systems with greater capacity, carefully prepared timelines to avoid excessive workloads, and more extensive crewman ground training. The successful development and improvement of the support equipment significantly increased the astronaut's capability to perform both intra- and extravehicular functions in zero and partial gravity environments. This increased capability, in effect, reduced the requirement for complicated, multipurpose tools for general repair and maintenance tasks. Once the astronaut was firmly restrained by tethers or foot restraint devices, the minimum reaction feature incorporated into many of the powered space tools lost much of its intended value.

The current design philosophy for spacecraft and equipment which may require periodic replacement or in-space maintenance is to design the vehicle/systems with ease of maintainability as a basic ground rule. This is being achieved through module/component replacement from on-board spares and

standardization of the tool interfaces required to service the spacecraft systems. The standardization of tool interfaces has simplified the problem of providing maintenance and service tools, particularly for intravehicular, first-level maintenance involving removal/replacement and limited in-place repair. Among the most important criteria in designating and designing tools for Skylab and future programs are design simplicity and the use, wherever possible, of standard, commercially available tools.

3.9.2 Tools and Aids for Orbital EVA Applications

Although very few of the special tools developed and tested have found on-orbit application to date, the requirement for a special tool(s) which incorporates some of the features previously developed may be needed on future missions. The purpose of this section is to present certain descriptive data and also the major physical and performance characteristics of tools previously designed specifically for orbital EVA use. These data will present the reader with an overview of the current tool development technology, should the requirement for similar space tools be identified. If special tools are needed, it is likely that their development will derive from only moderate modifications to existing space tools.

To present the tool data and characteristics effectively, the tools are classified as follows:

TOOL CLASSIFICATION

- Bonding and Electroadhesor Tools
- Cutting Tools
- Hammers
- Gas Leak and Pressure Detection Tools
- Electrical/Electronic Tools
- Screwdriving and Torquing Tools
- Tube Connection Tools
- Welders
- Tool Kits and Sets
- Special Application Tools

A general description of the tools developed in each of these classifications is presented in the following sections. Areas of application for these tools during EVA operations are included. Table 3-29 presents available information and general characteristics for several tools (refs. 3.35 and 3.36).

3.9.2.1 Bonding and Electroadhesor Tools

In order to perform work in a zero gravity environment, space suited astronauts will require restraints at the worksite. Bonding and electroadhesor

tools may provide attachment techniques important for space fabrication, maintenance, and translation tasks on future space missions.

Although electroadhesors and bonding tools employ many different principles, they have certain characteristics in common. They are designed to be used by themselves or in conjunction with booms or tethers, to provide a quick connect and disconnect capability, and not to damage the integrity of the associated object. They are quickly and easily applied almost anywhere on a space structure.

A representative example of an electroadhesor tool is the Hand Model Prototype (two-pole) Electroadhesor (see Figure 3-64) which was developed to examine the feasibility of using the electroadhesive principle for a remotely powered and controlled, quick connect and disconnect attachment device for IVA and EVA operations. Other methods of attaching temporary restraint devices to the spacecraft included chemically activated adhesives and exothermic epoxies.

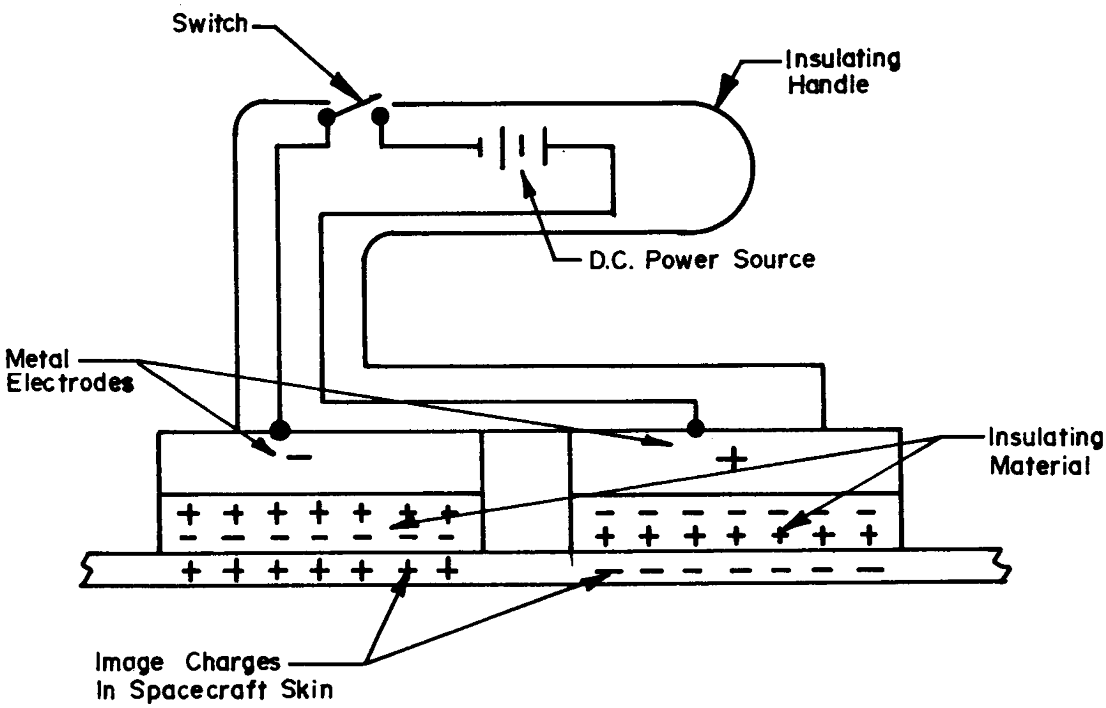


FIGURE 3-64: Hand Model Prototype (Two-Pole) Electroadhesor -- Principle of Operation

3.9.2.2 Cutting Tools

Various types of cutting tools may be required to perform future in-space maintenance and fabrication. The astronaut may need powered drills to cut holes for the placement of threaded fasteners, or he may require hole-saws

to permit the cutting of passage holes for pipes, cables, etc. Powered saws may also be required for on-the-spot cutting and fitting of metal sheets.

Although several space tools have been fabricated for these purposes, only those which appear to be applicable to future space missions were chosen for discussion. An example is the Power Saw (Figure 3-65) which was designed to cut metal sheets without requiring the astronaut to apply any forces beyond that of holding the power switch on and guiding the cut. Most cutting tools developed were of the powered type, designed to absorb reactive torque and apply pressure to the cutting blade. Examples of tools developed for cutting tasks include the power drill and saw attachments contained in the Martin Tool Kit, the S-IVB Workshop Window Saw Cutting Tool developed by Aircraft Armament, Inc., and the S-IVB Window Emplacement Tool developed by Hayes International Corporation. The Window Emplacement Tool incorporated a circular 10 grain/ft. explosive charge which, when placed against the vehicle skin section, blew a 6 in. diameter hole for external viewing.

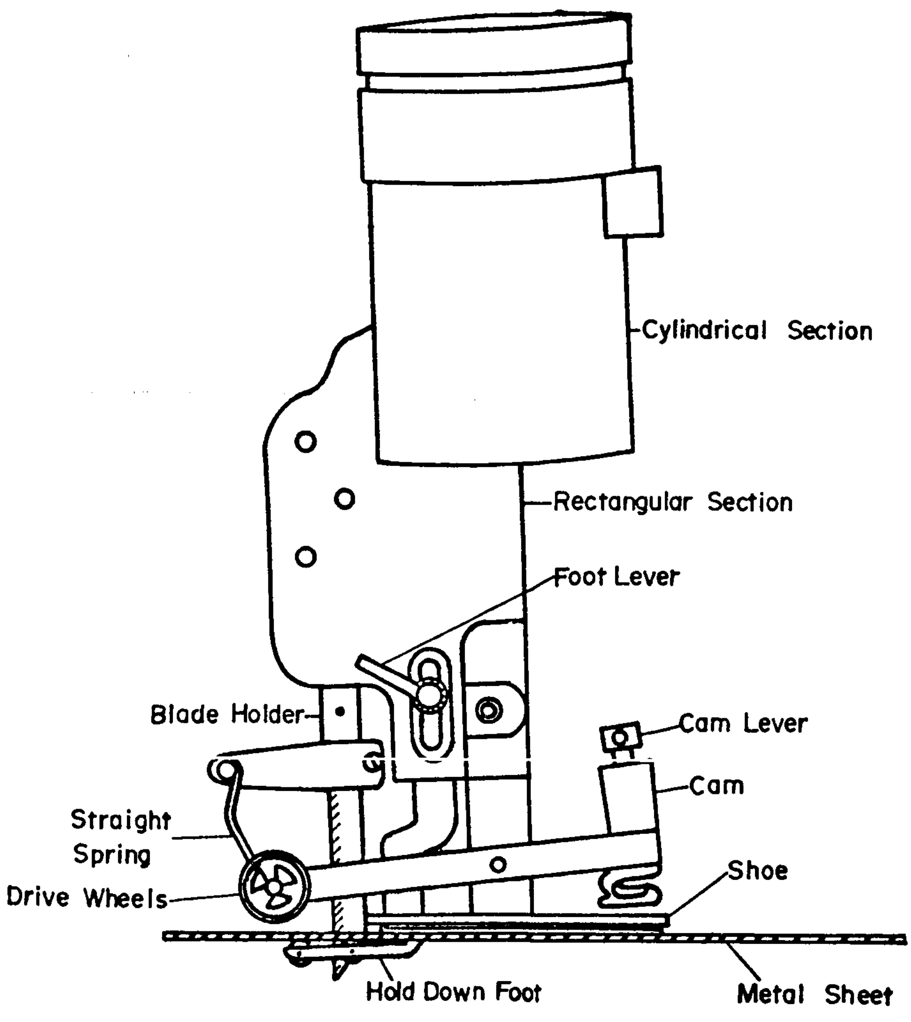


FIGURE 3-65: Power Saw

3.9.2.3 Hammers

Hammers for in-space use may be needed to assist the astronaut in construction operations requiring the placement of rivets and the driving of spike-type fasteners into the skin of space structures. The hammer may be used to drive a chisel head for cutting bolts, cables, or sheet metal, and it may be essential if repairs must be performed on metal panels damaged by collisions or distorted by welding operations.

Several space tools have been developed to exert a percussive force to free frozen parts, straighten metal objects, position tight fitting components, and drive cutting tools. Two hammers adapted for space use include a common ball-peen hammer and a "Lixie" soft face, dead blow hammer. The dead blow hammer is 75% filled with cast iron shot to minimize rebound and deliver more energy to the work (Figure 3-66). A powered, reactionless, impact tool (Figure 3-67) was developed by the Winchester Arms Corporation to function as a ball-peen hammer, chisel, and riveting tool. The tool is actuated by blank 22 cal. cartridges for delivering up to 140 ft. lbs. of energy to the workpiece.

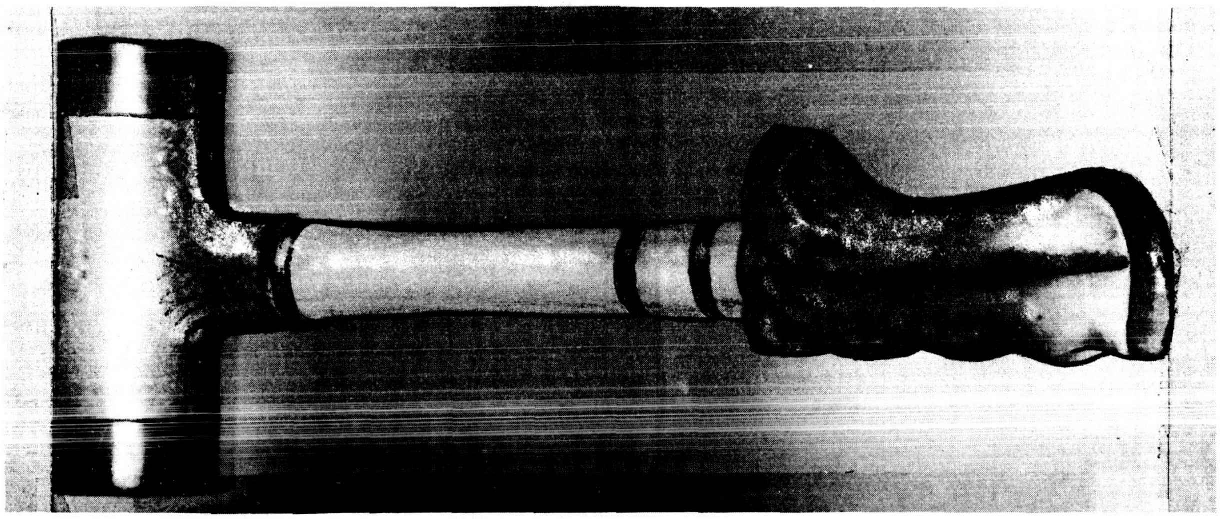


FIGURE 3-66: Dead Blow Hammer

3.9.2.4 Gas Leak and Pressure Detection Tools

Any space structure that will be manned for a long period of time cannot permit excessive air or fluid leaks. One of the most important requirements for in-space fabrication and maintenance will be the detection and measurement of such leaks. To accomplish this, small portable tools will be required to detect and measure gas and fluid leaks which may develop in the space structure's skin, joints, pipes, or tubing due to faulty construction, meteorite damage, or stresses incurred during space vehicle acceleration.

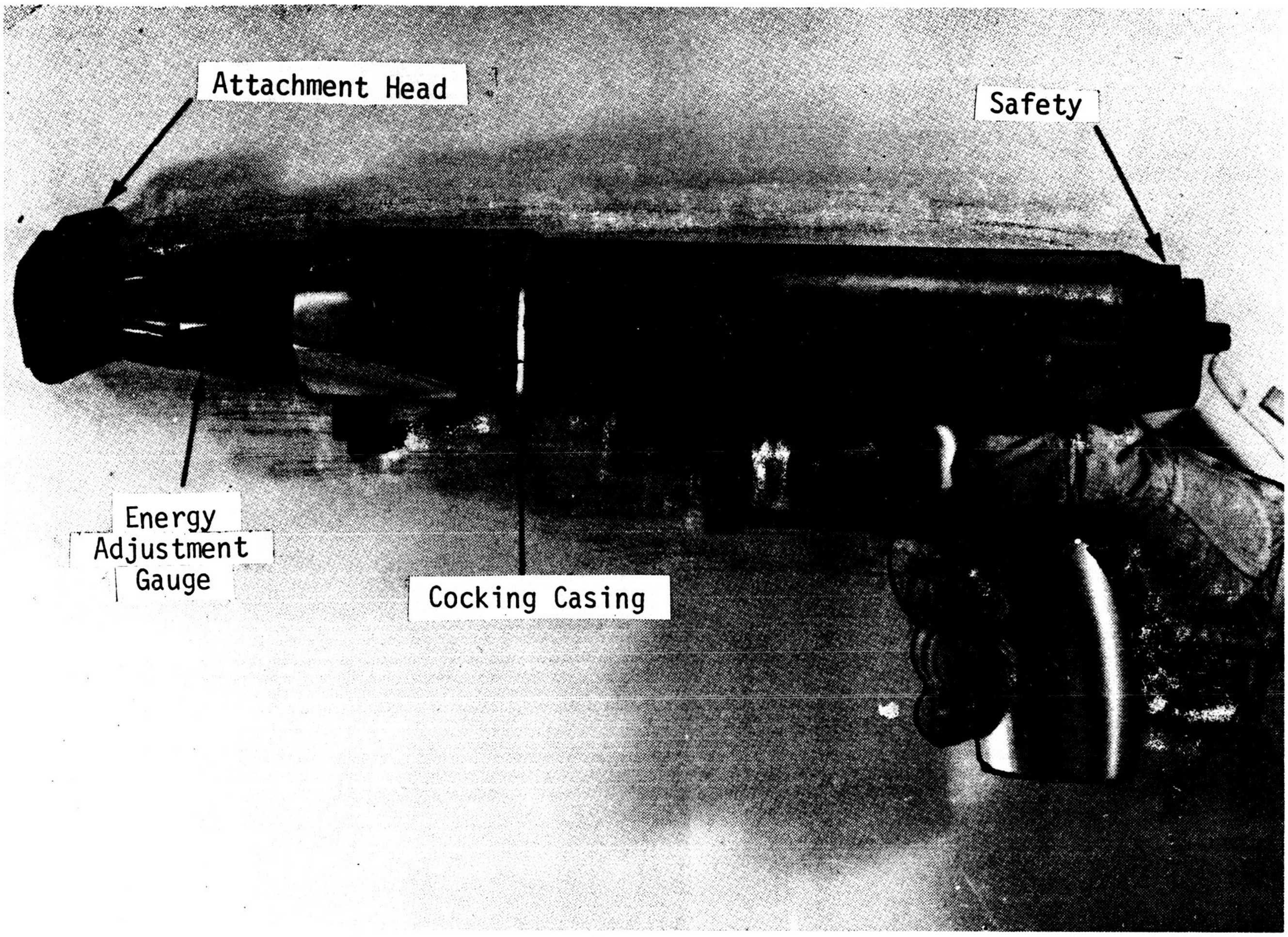


FIGURE 3-67: Space Impact Tool (Winchester)

An example of such a tool is the Mass Flowmeter (Figure 3-68) which was designed to measure flow rates discharging into space environment from leak or purge ports on aerospace hardware. A pilot model leak detector was designed as a hand held, hermetically sealed, self-powered instrument, capable of detecting gas leaks emanating from space systems/hardware and of measuring very low pressures.

3.9.2.5 Electrical/Electronic Tools

During manned space missions, the astronaut may be required to perform electrical repairing and check-out functions. The tools needed will be those designed for maintaining electrical and electronic equipment. Basically, some of these tools permit squeezing, holding and positioning electrical connections and small parts. Wire strippers, cutters, and crimpers will be used for removing insulation, cutting and joining wires. The Multipurpose Hand Wiring Tool (Figure 3-69) was developed to provide four modes of operation: common pliers, wire stripper, wire cutter, and wire crimper. Another tool

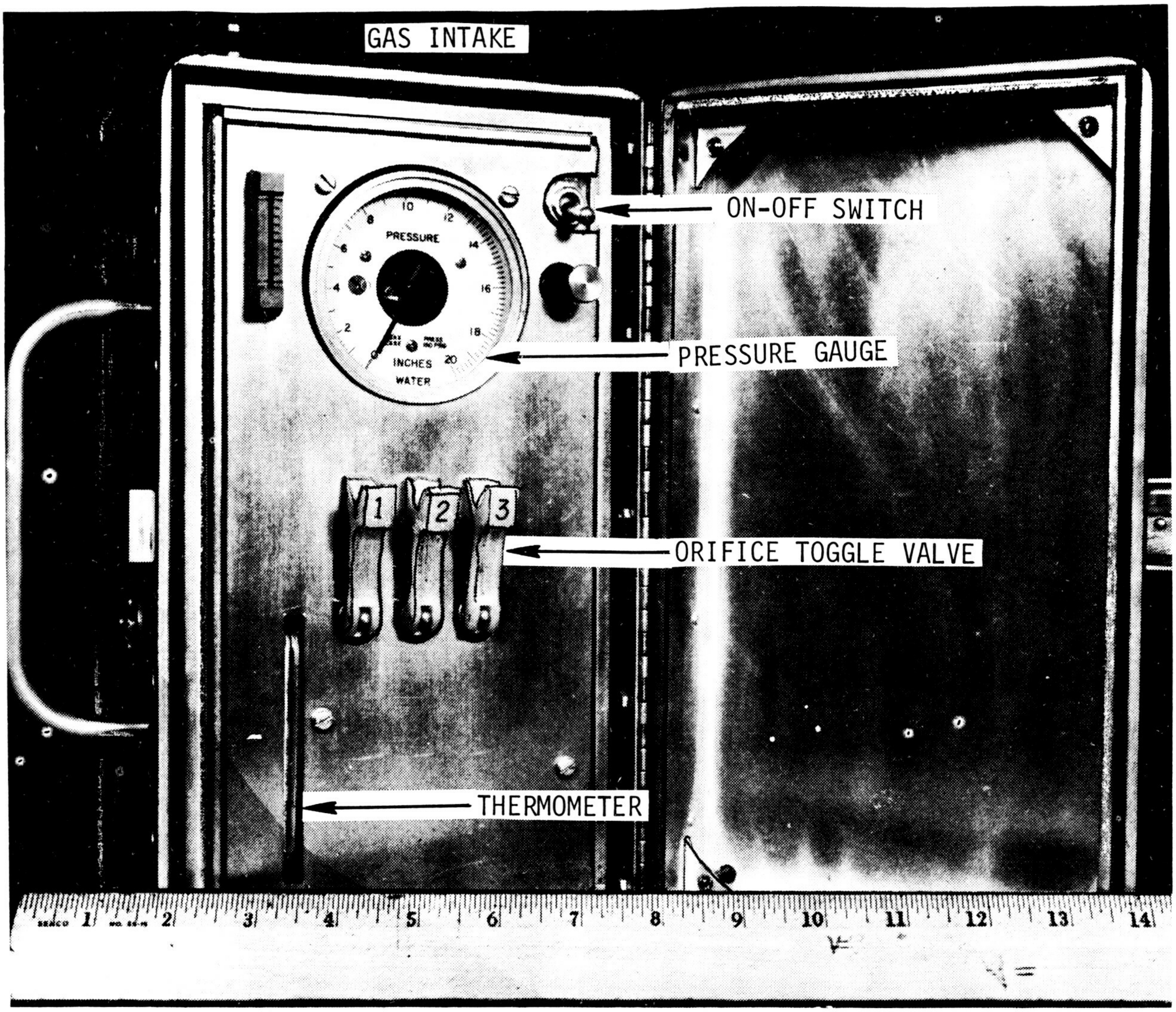


FIGURE 3-68: Mass Flowmeter

developed for electrical maintenance was a coaxial cable cutter to cut and strip coaxial cable quickly and accurately.

3.9.2.6 Screwdriving and Torquing Tools

Numerous tools have been designed to apply torque in a reduced-gravity environment for removing/installing bolts, hydraulic/pneumatic fittings, fasteners, etc. Many of these tools were developed to reduce reactive torque to the operator and to permit rapid nut/bolt running operations. There have been over thirty space tools developed to achieve screwdriving and torquing operations. A cross section of these tools is listed below:

- Aero Jet Space Bolt Removal Tool (BRT) - powered
- Apollo In-Flight Maintenance Tool, Figure 3-70 - manual

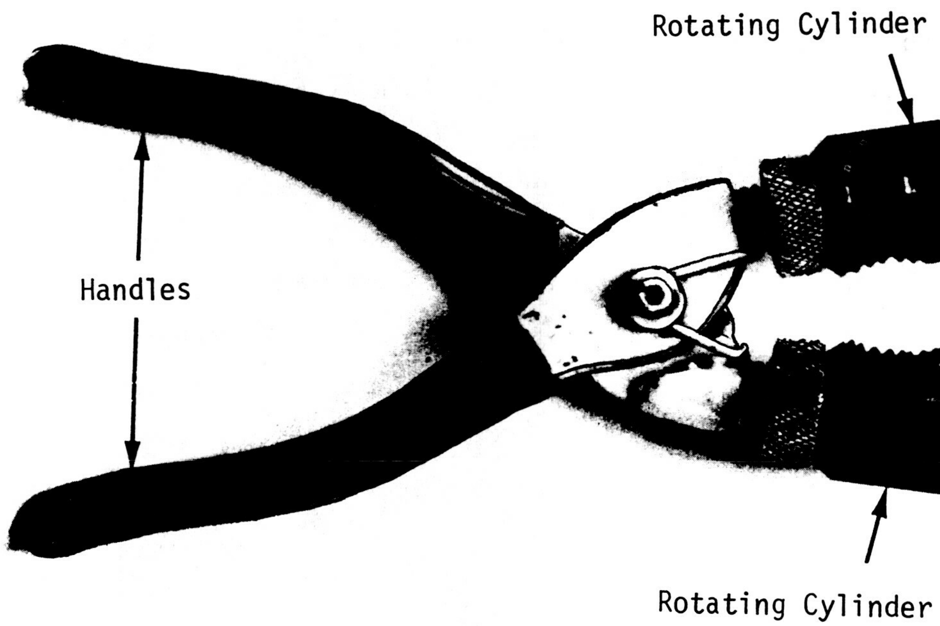


FIGURE 3-69: Multipurpose Hand Tool

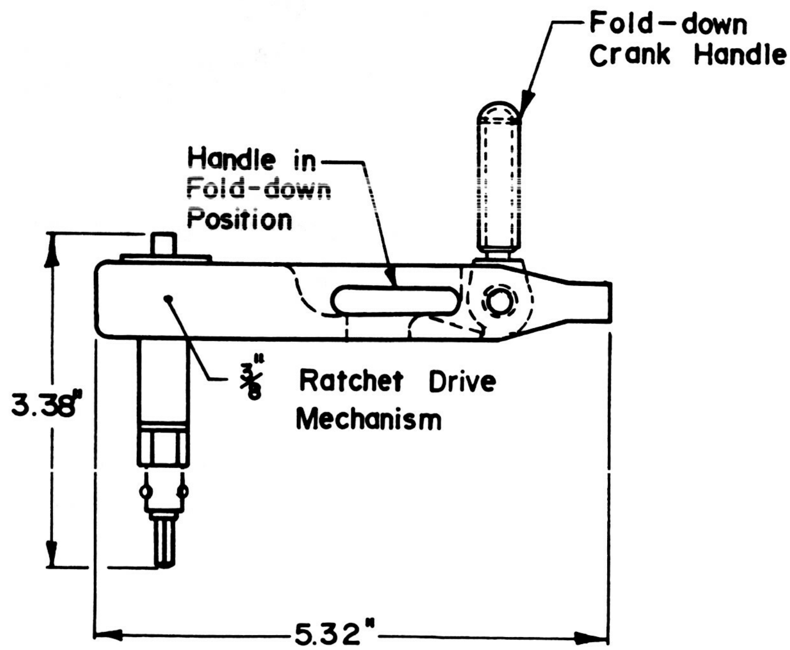


FIGURE 3-70: Apollo In-Flight Maintenance Tool

- Boeing Torque Cancelling Tool - manual
- Bolt Installation and Removal Tool (BIRT), Figure 3-71 - powered
- Inertia Wheel, Figure 3-72 - manual
- Space Powered Tool D-16, Figure 3-73 - powered
- Space Tool Mitten, Figure 3-74 - powered
- Spin Torque Space Tool, Figure 3-75 - powered
- T-Handle Multifunctional Tool, Figure 3-76 - manual

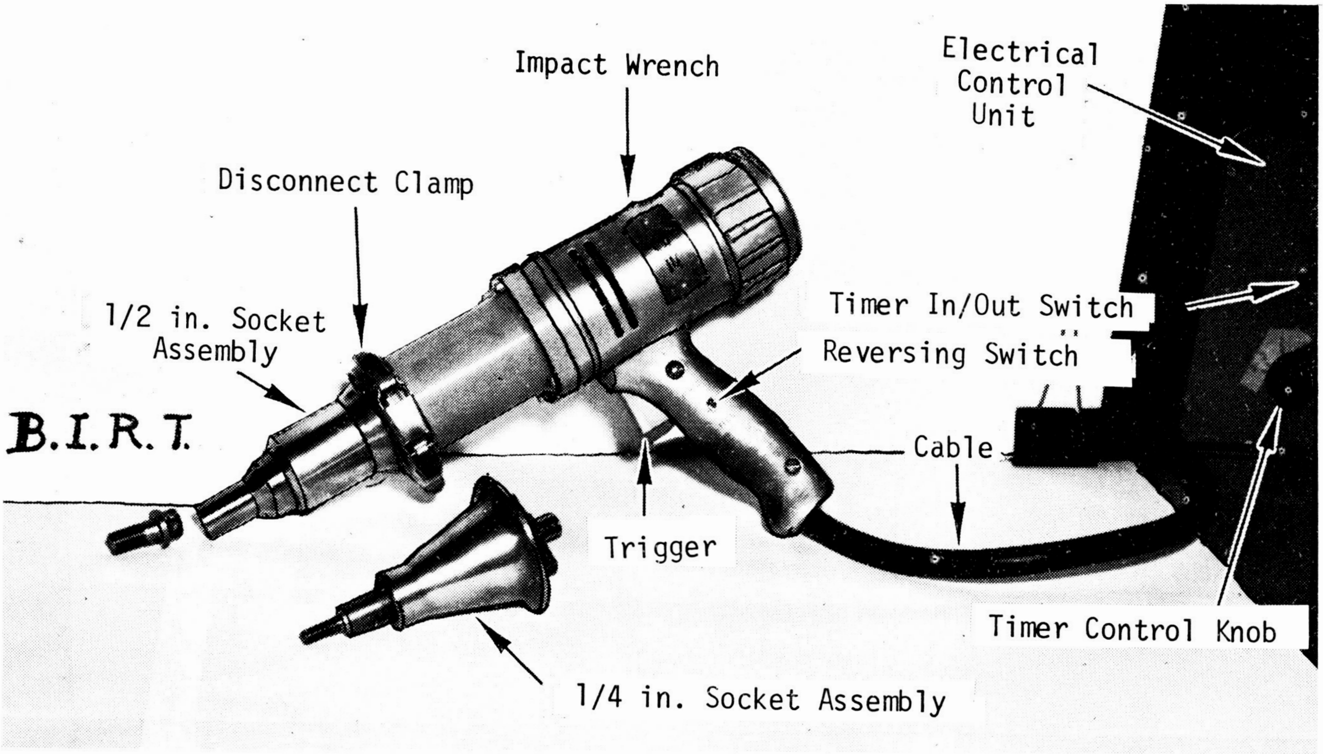


FIGURE 3-71: Bolt Installation and Removal Tool (BIRT)

3.9.2.7 Tube Connection Tools

The tubing systems in space vehicles of the future may suffer damage due to stresses and vibrations arising from vehicle accelerations or micrometeorite penetrations. Therefore, fabrication and repair capability will be required for tubing systems in space stations and for activities such as assembly in space. A basic task in the fabrication and repair of tubing systems is the connection of tubing sections. To fulfill this task, small portable tube connection tools will be required. A representative example of a tube connection tool is the Tube Swaging Device (Figure 3-77), which was designed to join a sleeve on two sections of tubing, providing a leak-proof, lightweight and strong connection.

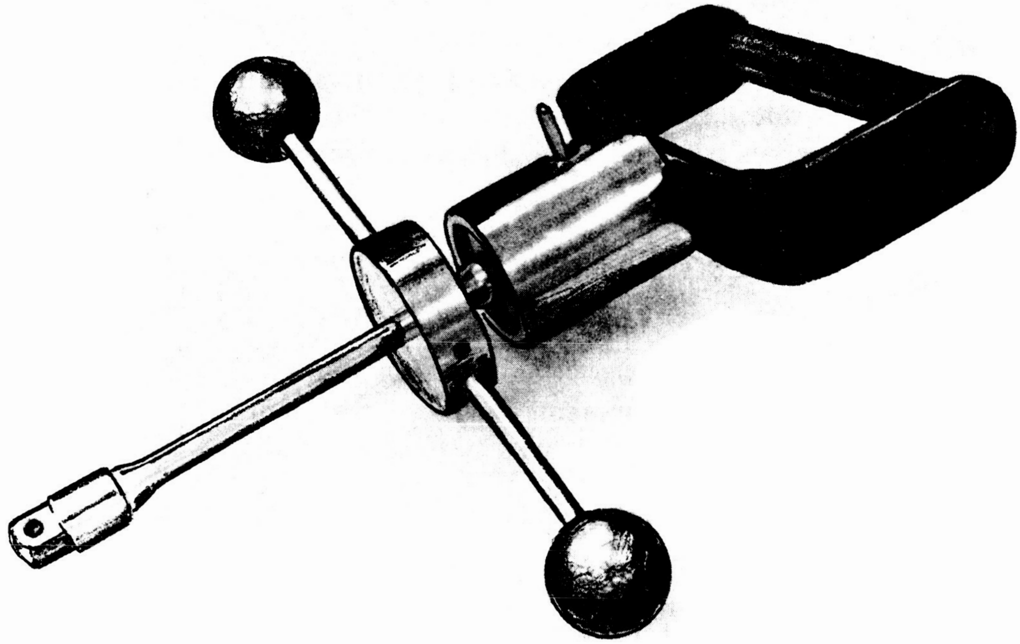


FIGURE 3-72: Inertia Wheel

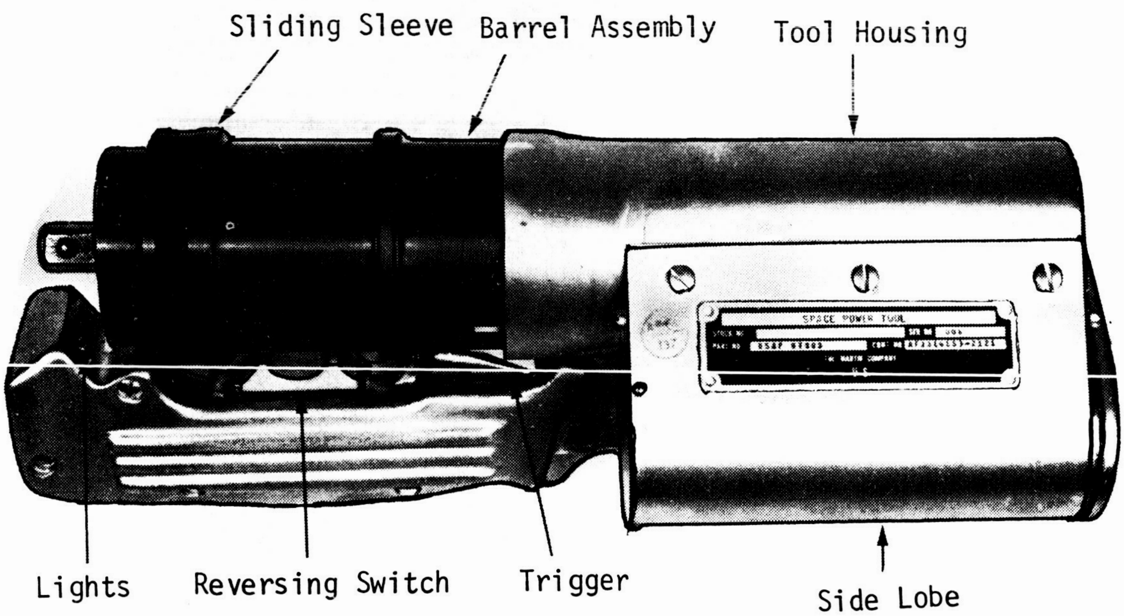


FIGURE 3-73: Space Powered Tool D-16

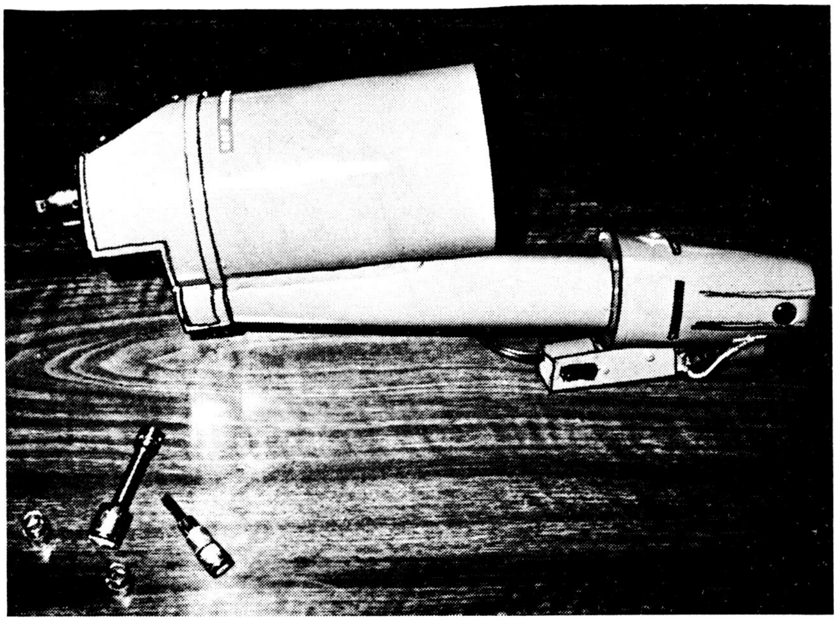


FIGURE 3-74: Space Tool Mitten

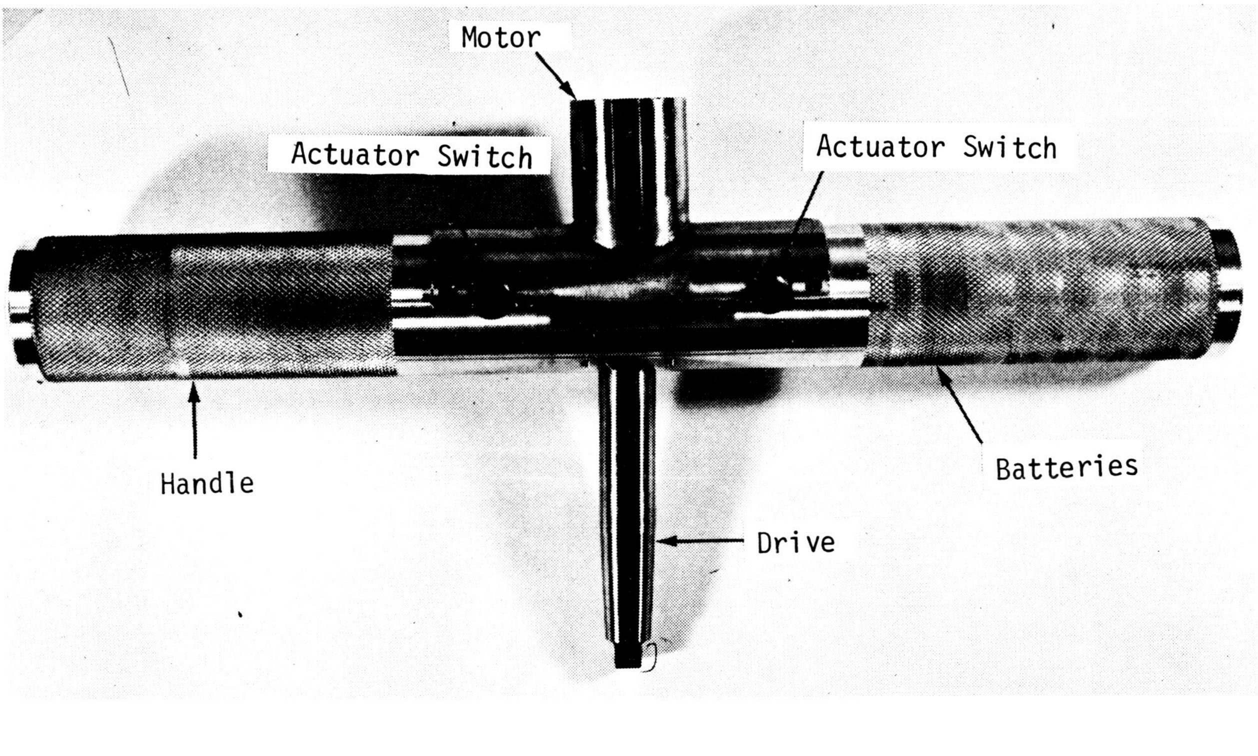


FIGURE 3-75: Spin Torque Space Tool

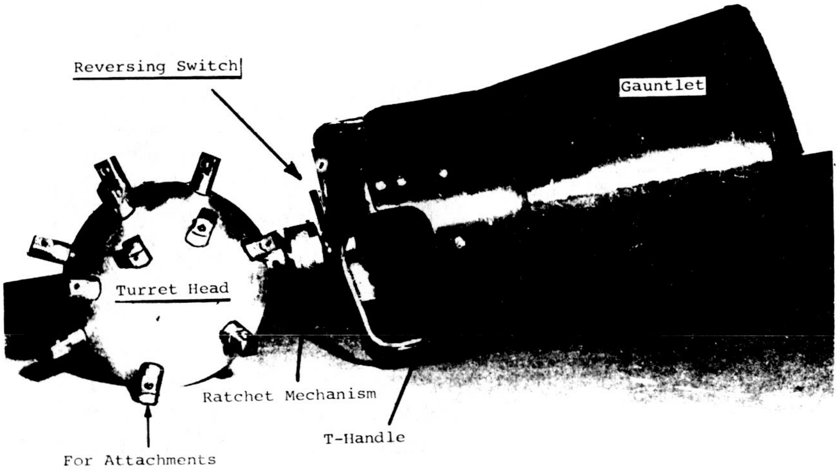


FIGURE 3-76: T-Handle Multifunctional Tool

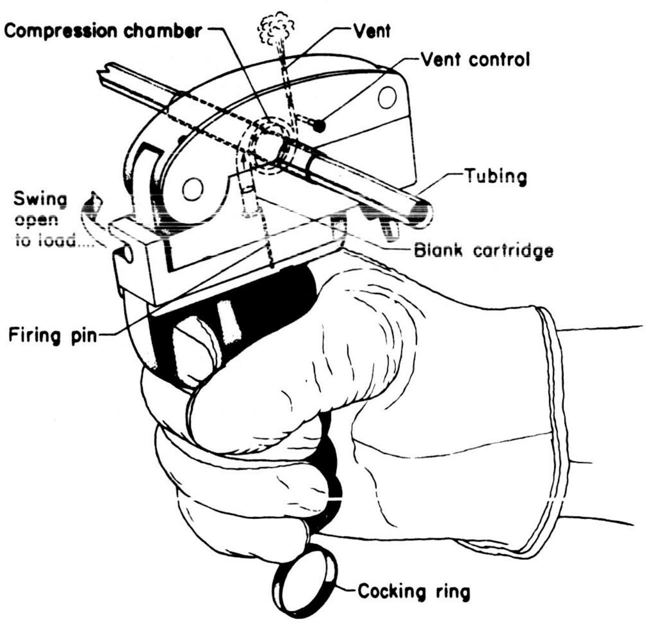


FIGURE 3-77: Tube Swaging Device

3.9.2.8 Welders

Any space structure that will be manned for a long period of time cannot permit excessive air or fluid leaks. Although many mechanical methods exist for the preparation of leak-tight joints, none can be compared to a welded joint. Therefore, welders may be one of the most important tools for in-space fabrication and maintenance. The Portable Electron-Beam Welder (Figure 3-78) was designed as a battery-operated, lightweight, portable welder for light welding jobs in space. Other portable welders, including the Plasma Electron-Beam Welder, the Hand Held Electron-Beam Welder, the materials joining tool, and the Westinghouse Electron-Beam Welder, were developed for on-orbit use.

3.9.2.9 Tool Kits and Sets

No single tool can handle all the fabrication and repair problems that an astronaut may meet in space. The astronaut will require a collection or set of tools designed to function as an integrated unit to give him a wide range of capabilities. Basically, a tool set can be particularly useful if it can be stored in a small, portable tool box to form a tool kit that can be carried by the astronaut to any worksite. An example of this form of tool kit is the Martin Space Tool Kit (Figure 3-79), which was designed to provide a set of tools with a small, portable tool container which would fulfill the minimum tool requirements for EVA and IVA repair and assembly tasks.

The tools required to support currently identified Skylab scheduled maintenance tasks are basically off-the-shelf hand tools. An allocation of sixty (60) lbs. is provided for maintenance tools for all Skylab maintenance operations. The tools are stored in two five-drawer removable containers located in the orbital workshop (OWS). The tool containers are designed to allow selection of a single tool from a drawer(s), or removal of the entire container for transport to the worksite. Each tool component is individually restrained in the containers and equipped with tether attachments of velcro patches to avoid loss during use. The tool kits (Figure 3-80) contain the following items:

- 1 Wrench, Adjustable
- 1 Pliers, Slip Joint
- 1 Pliers, Connector
- 1 Pliers, Needlenose
- 1 Pliers, Channel Lock
- 1 Cutter, Diagonal
- 1 Pin Straightener
- 1 Vise Grip
- 2 Screwdrivers, Standard
- 2 Screwdrivers, Phillips
- 1 Socket Wrench Set (15 pieces)
- 4 "C" Clamps
- 1 Mirror
- 1 Mechanical Fingers
- 1 Pinch Bar
- 1 Scissors
- 1 Crimper
- 7 Wrench, Open End/Box
- 1 Bench Vise
- 1 Spin Handle and 7 Allen Bits (plus 1 Square Bit)
- 1 Hammer, Ball-peen
- 3 Swiss Army Knives
- 2 Allen Wrenches
- Special Maintenance Tools

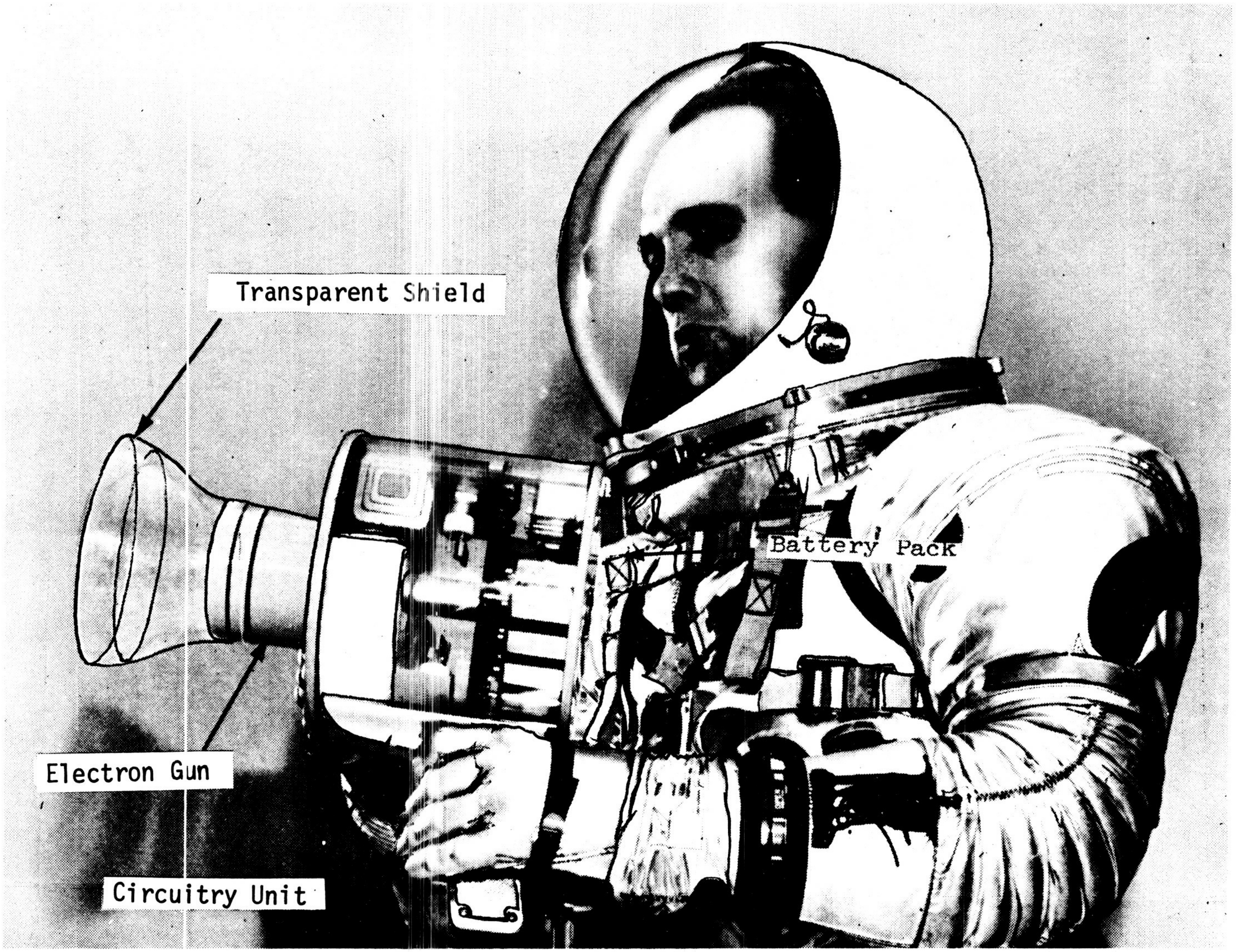


FIGURE 3-78: Portable Electron Beam Welder (0.5KW)

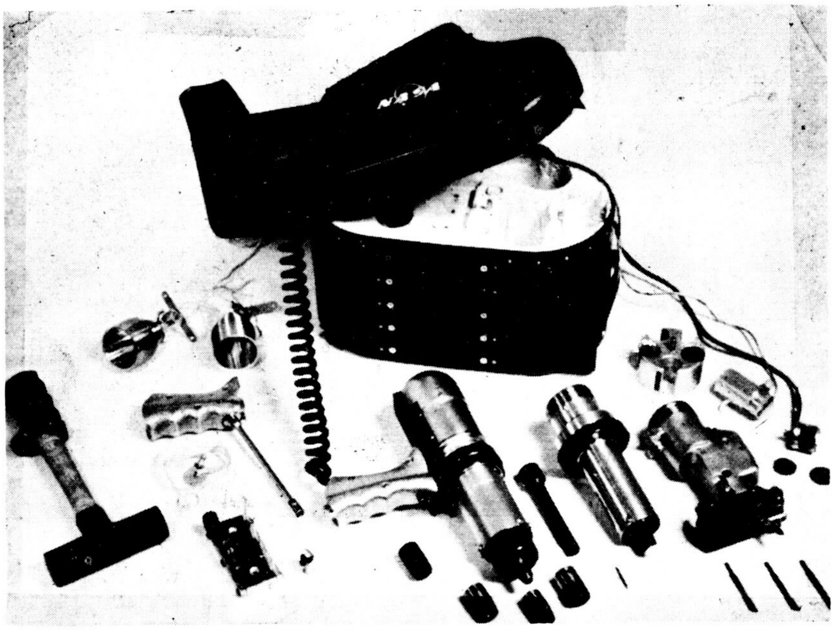


FIGURE 3-79: Martin Space Tool Kit

Special maintenance tools consist of items such as an O-ring extractor, tweezers, a terminal/splice kit, and wire insertion/removal tools. Other maintenance items include a multimeter (VOM), safety wire, lacing twine, velcro, electrical wire (12, 16, and 20 Ga.), general purpose tape, and a lubricant. An OWS repair kit is also included in the Skylab maintenance provisions. This kit is used for the repair of air ducts, curtains, filters and tank wall punctures. As was noted earlier, the Skylab systems and equipment that may require maintenance have been designed to be maintained through module or unit replacement using common hand tools. Powered tools, reduced or zero reaction tools, welders, special cutting tools, etc. appear unnecessary.

3.9.2.10 Special Application Tools and Equipment

Special application tools refer to those tools that aid the astronaut in overcoming unique problems so he may perform useful work. Such devices include illumination equipment, orientation and restraint tools, and maintenance equipment.

Among the more important problems that must be overcome if the astronaut is to perform useful work are those of orientation and restraint. The astronaut must support himself in a working attitude over the worksite and absorb the reactive torques transmitted to him from his tools. Also, his tools and associated gear must be restrained to prevent them from drifting away.

An astronaut boom attachment system was designed by the De Havilland Aircraft Corp. of Canada to provide a working attitude while performing

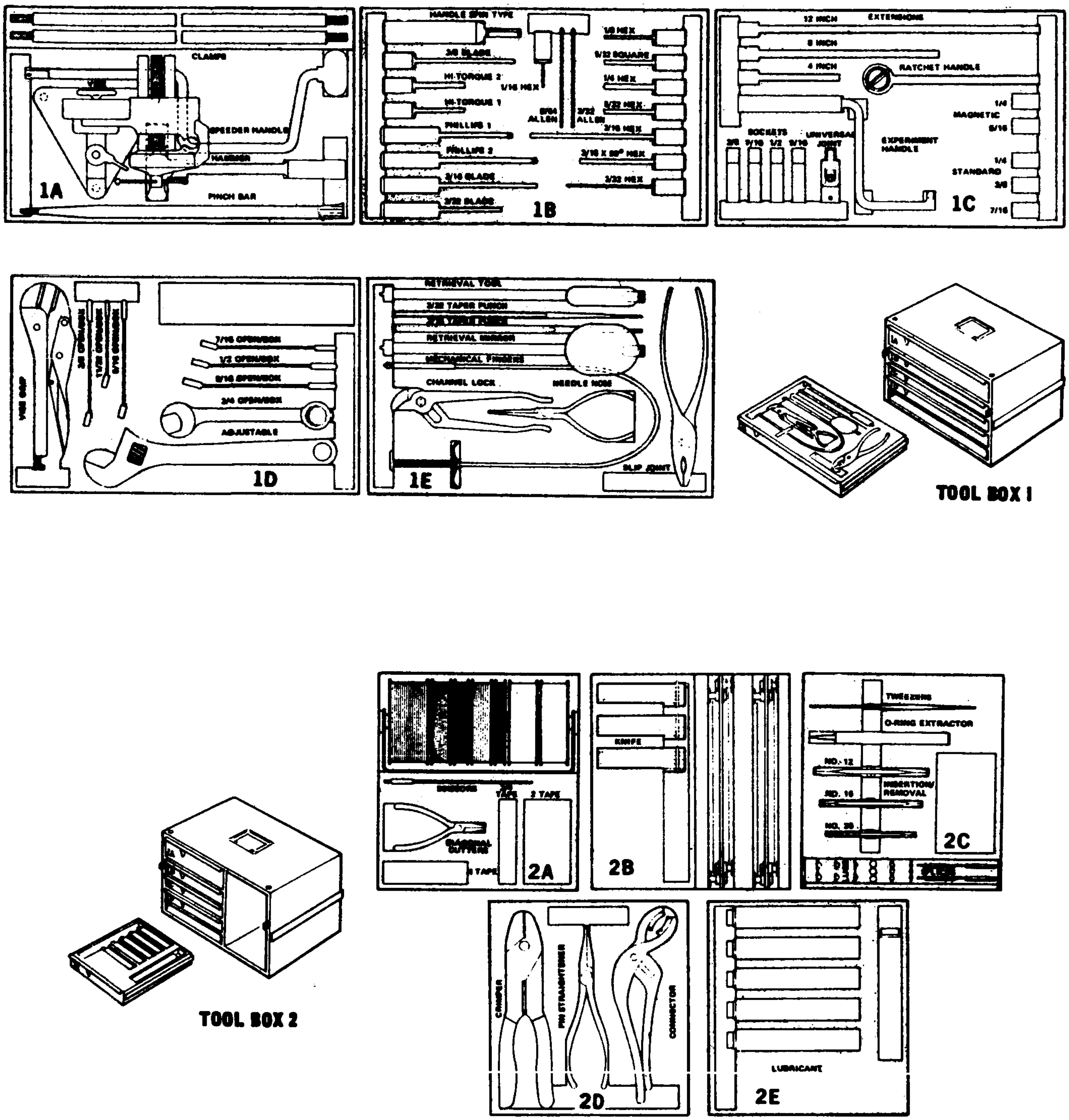


FIGURE 3-80: Skylab Maintenance Tool Kit

EVA maintenance (Figure 3-81). The system is a back pack unit with three extendible booms that can be extended or retracted individually or together. Other special application equipment includes the following:

- Variable Flexible Tether System
- Zero-gravity Surface and Interlocking Structure
- Rigid Rope
- Worklights
- KUPU Latch
- Lanyard System
- Positioning Tool
- Astronaut Boom Attachment System
- Tool Cuff System

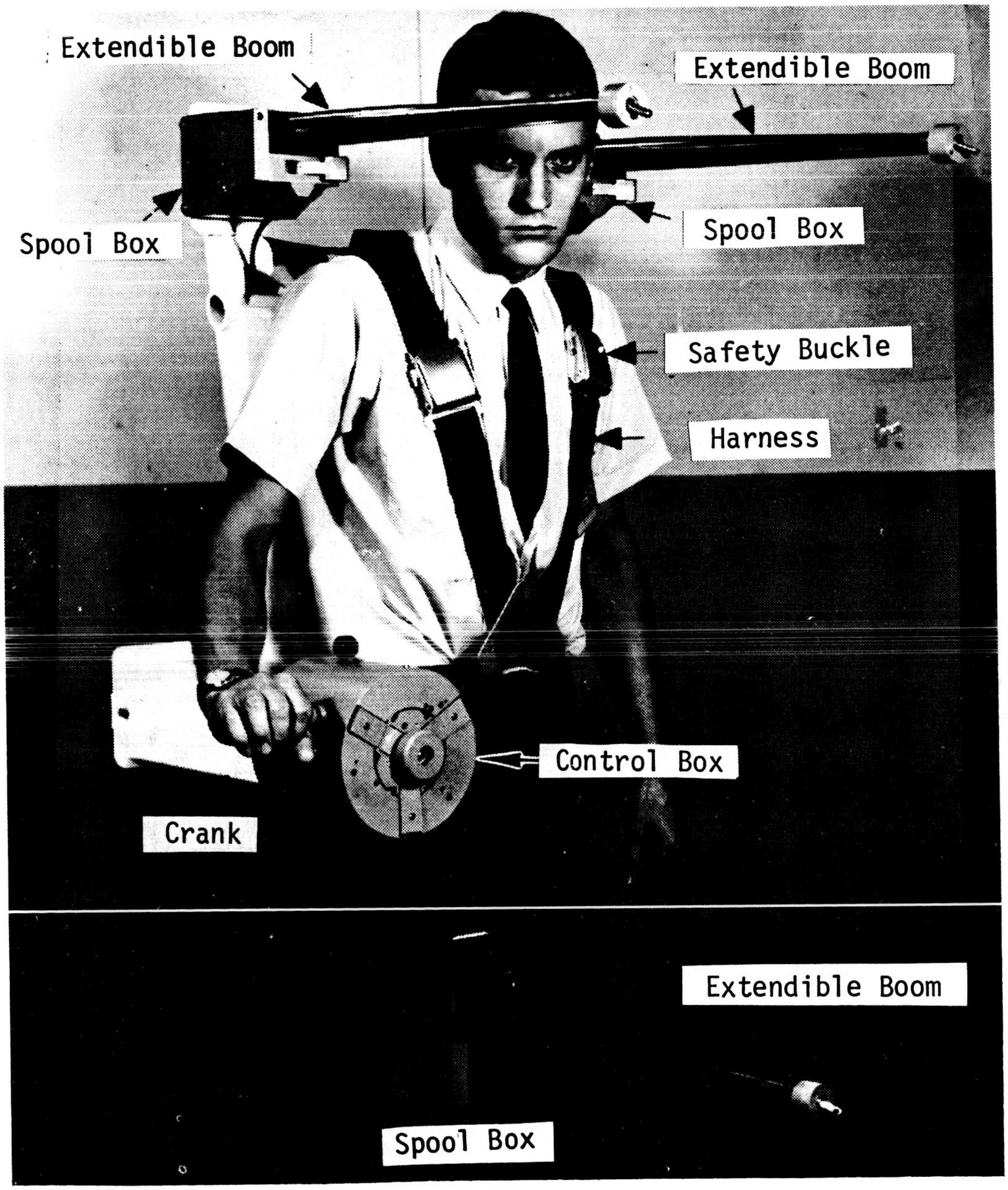


FIGURE 3-81: Astronaut Boom Attachment System

TABLE 3-29: Zero Gravity Work Aids

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
I. Bonding & Electroadhesor Tools			
a. Exothermic Space Bonding System	3" x 4.75" x 10.25"	< 5 lbs.	• Power requirements: 6 VDC nickel cadium cell • Hand transportable to site • Bonds to 123# tensile strength on aluminum • Works poorly on metal thicknesses below .012" • Metal must be preheated to 200°F before bonding occurs
b. Extravehicular Space Adhesive System	4.56" x 1.5" dia.	< 5 lbs.	• 2-5# force must be manually applied (compression) • Tensile strength 69# in 0 to 250°F temperature • Operates in vacuum up to 10^{-6} torr • Maximum life obtained when stored at @ 40°F • Manually operated (totally) • Hand transportable to site • Low resistance to peeling forces
c. Flexible Prototype (Single-pole) Electroadhesor	1" x 4" dia.	< 5 lbs.	• Bonds to 2# tensile & 1# shear strength • Requires 8.4 VDC (Mallory TR-126T2) battery • 30-40 hr. battery life (intermittent operation) • Hand transportable to site • Low resistance to peeling forces

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
I. Bonding & Electroadhesor Tools (cont.)			
d. Hand Model Prototype (Single-pole) Electroadhesor	<10" x 7" x 5" dia.	< 5 lbs.	• Bonds to 6# tensile and 40# shear loads • Requires 8.4 VDC battery (Mallory TR-126T2) • Low bond resistance to peeling forces • Operates on electro-conducting surfaces only • 30-40 hr. battery life (intermittent use) • Hand transportable to work site • Tool itself is the bonded hardware (for use as handhold, etc.) • Must be used on clean smooth surfaces
e. Hand Model (Two-pole) Electroadhesor	Unknown	2.5 lbs	• Same as d. above except as noted: • Bonds to accept 3# tensile and 18# shear loads
f. Restraint Buttons and Applicator	7" x 3" x 8"	0.75 lbs	• Withstands loads >50# when bonding temperature = 450°F • 11-90 sec. required to reach bonding temperature with aluminum sheets varying from 0.015" to 0.100" and various initial temperatures from -160°F to 70°F • Power source: 12 V Yardley HR-15 silver-zinc battery

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
I. Bonding & Electroadhesor Tools (cont.)			
g. Stud Bonding Tool	Unknown	2.5 lbs.	• Stud heated to as much as 707°F in 30 sec. • Stud cannot be released unless stud is applied perpendicular to the surface to be bonded • Holds up to 500# perpendicular to the bond line at room temperature • Power Source: 28 V, 1 kw
II. Cutting Tools			
a. Power Drill	8.25" x 3.25"	3.5 lbs.	• Drills holes 1/4" to 21/32" diameter in 0.040" 7075-T6 aluminum and 028 6-4 titanium in less than 34 sec. • Force required by astronaut: 0.5 lb.-sec. to initiate needle penetration • Needle travel and thus workpiece thickness is limited to 3/16" • Power source: motor/handle assembly provides the mechanical power to drive the drill
b. Power Saw	8" x 2.5" x 4"	3 lbs.	• No operator forces needed other than minor steering • Cuts at rates from 4 ft./min. in 0.016" 7075-T6 aluminum to 4 in./min in 0.100" 7075-T6 aluminum

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
II. Cutting Tools (cont.)			
b. Power Saw (cont.)			• Power source: motor/handles assembly provides the mechanical power to drive the saw
c. Window Saw Cutting Tool	7" x 6" x 14"	14 lbs.	• Operates satisfactorily under earth ambient conditions • Capable of cutting a hole in 1/8" 2014-T6 aluminum plate in 32 sec. • Power source: compressed air supply at 3,000 psi contained in a 7" sphere • 55-tooth cylindrical cutting blade driven at 0.667 rps • Cutting rate: 0.005" per revolution
III. Hammers			
a. Dead Blow Hammer	12.5" x 1.5" x 4.3"	1.75 lbs.	• Power source: manually operated • Hammering task best accomplished by using short, swift blows and gripping handhold
b. Winchester Space Tool	6" x 2"	7.68 lbs.	• Up to 140 ft.-lbs. of energy can be delivered to the work piece • Power source: modified 22 caliber Hornet cartridges
IV. Gas Leak and Pressure Detection Tools			
a. Mass Flowmeter	12.5" x 9.25" x 8.5"	7.75 lbs	• Measures flow rate of leaking gases

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
IV. Gas Leak and Pressure Detection Tools (cont.)			
a. Mass Flowmeter (cont.)			• Use restricted to outer space • Single crewmember operated • Internal power supply - 9 V battery • Includes several attachments to enhance tool applicability • Meets performance requirements that the meter should measure, within 90 sec., a leak of 0.006 to 0.67 stand. in.^{3}/sec. in a pressure environment of 1.93×10^{-5} to 1.33×10^{-15} psi with an error not to exceed 5%
b. Pilot Model Leak Detector	8.3" x 8.3" x 7.8"	6.3 lbs.	• Self-contained power supply (28 V battery) • Measures gas leaks • One-handed operation • Measures pressures from 10^{-10} to 10^{-4} torr • Detects leaks 6.17×10^{-8} stand. in.^{3}/sec.
V. Electrical/Electronic Tools			
a. Coaxial Cable Cutters	6" x $\approx$ 1"	<5 lbs.	• Manually operated
b. Multipurpose Hand Wiring Tool	Unknown	Unknown	• Manually operated • Functions as pliers, wire stripper, wire cutter and wire crimper

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
V. Electrical/Electronic Tools (cont.)			
c. Program Control Card Extractor System	7" x 7" x 1.5"	Unknown	• Manually operated
VI. Screwdriving and Torquing Tools			
a. Aero Jet Space Bolt Removal Tool	4.25"x10.75"x20.32"	19 lbs.	• Retraction unit equipped with a socket sized for 5/16", 12-point head bolts • Right angle drive transmits torque around corners • Removes bolts torqued to 145-155 in.-lbs. • Power source: 12 VDC
b. Apollo Adjustable End Wrench	10" x 2"	< 2 lbs.	• Jaws adjustable to any size between 3/8" to 1" • Jaws lock into position when torque is applied • Manually operated
c. Apollo In-Flight Maintenance Tool	5.32" x 3.38"	< 5 lbs.	• Equipped with 22.12", 13.62", and 4.00" length male hexagonal wrench attachments • Loosens and tightens clamps, mounting bolts, and CALFAX Fasteners • Equipped with card extractor • Manually operated

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
VI. Screwdriving and Torquing Tools (cont.)			
d. Apollo T-Handle	≈2.1" x 3.11"	< 5 lbs.	• 3/8" ball lock and 5/32" male hexagonal wrench tip located at bottom of drive shaft • Manually operated
e. Apollo Torque Wrench	6.25" x 1.5" x 0.75"	< 5 lbs.	• Torque can be pre-set by rotating handle in unit turns of 180° • Torque ranges: 50, 100, 150, and 200 in.-lbs. • Drive end consists of 7/16" and 5/32" male hexagonal wrench heads • Direction in which the wrench ratchets controlled by ratchet lever • Manually operated
f. Boeing Torque Cancelling Tool	22" x 14" x 3"	< 5 lbs.	• Reaction forces are opposed and tend to cancel one another • Various sized sockets can be used with tool • Manually operated
g. Bolt Installation and Removal Tool (BIRT)	15 1/2"x 5"x3 1/8"	10 lbs.	• Impacting cycle can be set for 0-30 sec. • With 5/16" socket, 140-200 in.-lbs. torque can be produced in 5 sec. on bolt #MS21250H05004 • With 1/2" socket, 700-950 in.-lbs. torque can be produced in 5 sec. on bolt #MS21250H08804 • Power source: external 12 VDC with 50 amp. current capacity

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
VI. Screwdriving and Torquing Tools (cont.)			
g. Bolt Installation and Removal Tool (BIRT) (cont.)			• Equipped with 1/4", 5/16", 3/8", 7/16", and 1/2" socket assemblies
h. Inertia Wheel	13" x 9.5"	5 lbs.	• 3/8" square drive located on drive shaft • Low amount of rotational motion required for operation • Manually operated • Various sized sockets can be used with tool
i. Motor/Handle Assembly	7.0" x 3.0" x 8.0"	5 5/8 lbs.	• Easily transportable to worksite • Difficult to attach or remove • Separately contained 12 VDC battery
j. Nut & Bolt Wrench (NAB)	Unknown	Unknown	• No data exists • Serves as ratcheting non-torque cancelling two-hand held tool
k. Open End Flat Ratchet Wrench	17" x .6" x 6"	3 lbs.	• Manually operated • Easily transported to worksite • Can engage nut or bolt in 15° increments about full 360° of shank • Can withstand 660 in.-lbs. torque • Human operator can apply 75 in.-lbs. with hand squeeze • Will fit ≥ 1/2" bolts • Will accept bolt drives of various sizes

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
VI. Screwdriving and Torquing Tools (cont.)			
l. Pliers-Wrench (Plench)	Unknown	Unknown	• Manually operated • Multiple socket versatility • Hand squeeze operated
m. Power Impact Wrench	6.4" x 2 1/4" dia.	2 5/8 lbs.	• Requires coupling to motor handle assembly (described elsewhere) • Accepts 5 1/2" drive sockets • Maximum torque 85 ft.-lbs. in 3 sec. • Maximum handle torque reactance requirements 5.6 in.-ozs. • Crew transportable to worksite
n. Ratchet Hand Tool	Unknown	.2 lbs.	• Hand operation, non-torque cancelling nut & bolt ratchet • Crew transportable to worksite
o. Screwdriver Ratchet Handle	4.6" x 1.4" x 2.7"	.75 lbs.	• Manually operated, non-torque cancelling • Crew transportable to worksite • Uses standard 1/4" drive accessories
p. Space Power Tool System	10 13/16"x4 1/2"x5"	7.62 lbs.	• Internal power supply (battery) • Crew transportable to worksite • Self-contained work areas illuminating • Torque output = 45 ft.-lbs. on 1/2" bolt • Impact driver

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
VI. Screwdriving and Torquing Tools (cont.)			
q. Space Tool Mitten	16.4" x 5" x 8.1"	9.7 lbs.	• Self-contained power supply (battery) • Delivers 200 in.-lbs. to 1/2" fastener • Provides suit glove protection • Accepts standard 1/4" drive • Impact driver • Crew transportable to worksite
r. Spin Torque Space Tool	16 3/4" x 2" x 11"	6 lbs.	• Either manually or electrically driven • Battery life expectancy - 1 hour • Non-torque cancelling • Two-handed operation • Standard 3/8" drive • Crew transportable to worksite
s. Spiral Drive Screwdriver	Unknown	Unknown	• 1/4" drive • Insignificant output for required input • Manually operated • Crew transportable
t. Zero Reaction Space Wrench	Unknown	< 10 lbs.	• Manually hand squeeze operated • Torque cancelling • Crew transportable
VII. Tube Connection Tools			
a. Semiremote Spunfit Wrench	Unknown	Unknown	• Manually operated scissor motion (two arms)

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
VII. Tube Connection Tools (cont.)			
a. Semiremote Spunfit Wrench (cont.)			• Crew transportable
b. Spunfit Wrench	Unknown	Unknown	• For use on hexagonal head connectors • Manually operated • Crew transportable
c. Tube Swaging Device	Unknown	Unknown	• Powered by 22 caliber blank cartridge • Restricted usage • Crew transportable to worksite
VIII. Welders			
a. Hand Held Electron Beam Gun	3.5" dia, x 10"	10 lbs.	• Unable to move >50' from power source • Welds 15 in./min. in aluminum-titanium-stainless up to .125" thick • Needs 20 kv at 150 ma power supply
b. Materials Joining Tool	6.0" x 2" x 3"	9.5 lbs.	• External power source • Needs 7.5 kv at 300 ma power supply • Must be used in vicinity of power supply • Spot welds acceptable in materials up to .06" thick • Circular welds on tubing up to .4" dia. were satisfactory on stainless, copper, titanium

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
VIII. Welders (cont.)			
b. Materials Joining Tool (cont.)			• Unsatisfactory performance on aluminum
c. Plasma Electron Beam Welder	Unknown	Unknown	• External power source requirement = 10V @ 2 kw • Welds to 1/4" thick 6061 aluminum • Welding rate up to 20 in./min. • Internal power supply (battery) • Crew transportable to worksite
d. Portable Electron Beam Welder (0.5 kw)	14" long x 13" dia.	45 lbs.	• Self-contained power supply (battery) • Crew transportable to worksite • Short battery life
e. Westinghouse Electron Beam Welder	21" x 12" x 10"	61 lbs.	• Internal/external power supply (battery) 35V DC - 70 amp requirements • Welds 1/8" 18-8 stainless at 37 in./min. • X-ray shielding must be provided • Crew transportable to worksite
IX. Tool Kits and Sets			
a. Crewman Inflight Tool Set	Unknown	2.88 lbs	• Includes following items covered elsewhere - Apollo torque wrench - Apollo t-handle - Apollo adjustable wrench

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
IX. Tool Kits and Sets (cont.)			
b. Martin Space Tool Kits	9.5" x 14.5"x 14.5"	38 lbs.	• Includes 12V DC battery pack 163 watt-hrs. @ 40 amp • Includes Martin tool kit case (includes power supply) • Includes following tools covered elsewhere - dead blow hammer - motor/handle assembly - power drill - screwdriver ratchet handle - worklights - power impact wrench - power saw - restraint buttons & applicator - small parts holder/manipulator • Removal-replacement of tools difficult
X. Special Applications Tools			
a. Worklights	4" long x 2.2" dia.	.87 lbs.	• External power supply (12V DC) • Astronaut helmet mounted
b. Astronaut Boom Attachment System	volume = @ 1600 $in.^3$	Unknown	• Withstands 45 ft.-lbs. with boom extended 2.75 ft. • Utilizes 3 STEM's • Manually operated

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
X. Special Applications Tools (cont.)			
c. Extendible Boom	Unknown	Unknown	• Manually/electrically operated
d. KUPU Latch	5" x 5" x 1/2"	3/4 lbs.	• Manually operated • 6000# tensile strength • Provides eyelet useful for attachment of restraints and tethers
e. Lanyard System	Unknown	Unknown	• Manually operated • Functions as restraint or tether (flexible)
f. Positioning Tool	32" extended length	Unknown	• Manually operated • 200# compression force strength • Functions as a hard restraint system
g. Rigid Rope	Unknown	Unknown	• Manually operated • Functions as either hard or flexible tether • Withstand 100 ft.-lbs. torque
h. Small Parts Holder	Unknown	Unknown	• Provides up to 8 anchorages for small parts
i. Small Parts Manipulator (Fingernail)	Unknown	Unknown	• Manually operated • Functions as artificial fingernail (over gloved hand)
j. Tool Cuff System	6 3/8"x2 5/8"x1 3/8"	Unknown	• Functions as suit attached tool holder • Contains 9 separate holder compartments

TABLE 3-29: Zero Gravity Work Aids (Cont'd.)

TOOL CATEGORY	SIZE/VOLUME	WEIGHT	PERFORMANCE CHARACTERISTICS
X. Special Applications Tools (cont.)			
k. Variable Flexibility Tether System	8' x 2" dia.	22#	● Manually operated ● Generate 21# tip force ● Withstands 61 ft.-lbs. torque
l. Zero Gravity Surface and Interlocking Structure	Unknown	Unknown	● Functions as hermaphroditic surface to hold tools

REFERENCES

3.1 NASA: Summary of Gemini Extravehicular Activity, NASA-SP-149, Washington, D.C., 1967.

3.2 NASA: Gemini Summary Conference, NASA-SP-138, Washington, D.C., 1969.

3.3 North American Rockwell Corp.: Extravehicular Engineering Activities (EVEA) Program Requirements Study, SC 68-304-2, May 1968.

3.4 NASA: Minutes of the NASA Committee on Extravehicular Activities Meeting #69-2, July 1969.

3.5 NASA: Minutes of the NASA Committee on Extravehicular Activities Meeting #69-3, November 1969.

3.6 Bellcomm, Inc.: EVA/IVA Life Support Equipment for AAP, ML Action Item 478, Washington, D.C., December 1968.

3.7 Hamilton Standard: Apollo Portable Life Support and Oxygen Purge Systems, B-231A, Windsor Locks, Conn., (no date).

3.8 NASA: Minutes of the NASA Committee on Extravehicular Activities Meeting #71-1, April 1971.

3.9 Martin Marietta Corp.: Skylab Operations Handbook, Contract No. NAS8-2400, Houston, Tex., July 19, 1971.

3.10 Manned Spacecraft Center: Skylab Operational Data Book, Vol. V, MSC-01549, Houston, Tex., October 1970.

3.11 Hamilton Standard: Advanced Extravehicular Protective System, Interim Report, Windsor Locks, Conn., July 1970.

3.12 Matrix Research: Selection of Systems to Perform Extravehicular Activities, Man and Manipulator, Final Report, Vol. 2, Contract No. NAS8-24384, Huntsville, Ala., April 9, 1970.

3.13 Manned Spacecraft Center: Skylab Extravehicular Mobility Unit, Master End Item Specification Performance and Design Requirements, CSD-S-014, MSC-028D6, Houston, Tex., October 6, 1971.

3.14 AiResearch Manufacturing Co.: Advanced Extravehicular Space Suit (AES), Final Report, Contract No. NAS9-7555, Los Angeles, Calif., August 17, 1970.

3.15 Howard, D. C. Integrated Maneuvering Life Support System, Contract No. F33615-67-C-1946, Hamilton Standard, Windsor Locks, Conn., March 1970.

3.16 AiResearch Manufacturing Co.: Torso-Limb Assembly (TLA) for Advanced Extravehicular Space Suit (AES), Master End Item/Contract End Item Specification (Prime Equipment), Part I, MEI/CEI No. 958567A, Contract No. NAS9-7555, January 15, 1970.

3.17 ILC Industries, Inc.: A7LB Pressure Garment Assembly with Integrated Thermal Meteoroid Garment for Apollo Extravehicular Mobility Unit, Contract End Item Specification (Prime Equipment), CEI No. 3001 B, Rev. A, Dover, Del., January 30, 1970.

3.18 Litton Systems, Inc.: Torso Limb Assembly (TLA) for Advanced Extravehicular Space Suit (AES), Part I: Performance Design Requirements, Master End Item/Contract End Item Detail Specification (Prime Equipment), CEI No. SD08, Spec. No. 241901, Contract No. NAS9-7533, Feburary 16, 1970.

3.19 Manned Spacecraft Center: Model A7L Space Suit, Apollo Block II, Contract End Items Familiarization and Operations Manual, Contract No. NAS9-6100, Doc. #8812700149A, Houston, Tex., November 21, 1968.

3.20 ILC Industries, Inc.: Model A7L Advanced Extravehicular Pressure Garment Assembly, unpublished presentation, 1969.

3.21 Manned Spacecraft Center: Extravehicular Mobility Unit for Lunar Module Crewman (EMU/LM) Apollo J-Missions, Master End Item Specification Performance/Design and Product Configuration Requirements, CDS-A1059, Houston, Tex., May 1968.

3.22 McDonnell Douglas Astronautics Co., Eastern Div.: Airlock Design Data Book, July 1970.

3.23 Manned Spacecraft Center: Preliminary Design Requirements for Shuttle EVA/IVA Orbiter Support, NASA Internal Note MSC-EC-71-10, Document No. MSC 01497, September 1971.

3.24 Manned Spacecraft Center: Preliminary Requirements for Airlocks on Space Stations, CSD-SS-010, NASA, Crew Systems Division, Houston, Tex., Feburary 1972.

3.25 Bell Aerospace Co.: Astronaut Maneuvering Unit Brassboard, Final Report, Contract No. NAS9-9368, SSD-206, March 1970.

3.26 NASA: Reference Earth Orbital Research and Applications (Blue Book), NHB-7150.1, January 15, 1971.

3.27 "The Bi-stem -- A New Technique in Unfurlable Structures", Second Aerospace Mechanisms Symposium, Preprint No. 18, May 1967.

3.28 Reinrott, F. P. "Storable Tubular Extendible Member -- A Unique Machine Element", Machine Design, December 1965.

3.29 Wheelwright, C. W. General Specifications for Spacecraft Lighting, SC-L-0002, Manned Spacecraft Center, Houston, Tex., November 1971.

3.30 Weippert, J. J. and R. E. Donaughy. "Apollo EVA Communications Telemetry Subsystem", Conference of the International Foundation for Telemetry, Washington, D.C., September 15-17, 1969.

3.31 McDonnel Douglas Astronautics Co.: Airlock Critical Design Review: Communications System, August 10, 1970

3.32 NASA: Biomedical Research and Computer Application in Manned Space Flight, NASA-SP-5078, J. F. Lindsey and John C. Townsend (eds.), Washington, D.C., 1970.

3.33 Martin Marietta Corp.: Skylab Program, a Detailed Summary for Operational Bioinstrumentation System, Contract No. NAS8-2400, Martin Marietta Denver Div., February 22, 1971.

3.34 McDonnell Douglas Astronautics Co.: Airlock Critical Design Review: Instrumentation System, August 10, 1970.

3.35 Raff Associates: NASA List of Potential Space Tools and Equipment, Contract No. NAS2-5073, Report No. CR-1760, May 1971.

3.36 U. S. Air Force Aero Propulsion Laboratory and the Martin Co.: National Conference on Space Maintenance and Extravehicular Activities, March 1966.

CHAPTER IV

EVA SYSTEMS DEVELOPMENT CONSIDERATIONS

TABLE OF CONTENTS

4.0 INTRODUCTION

In addition to the previously discussed EVA systems, support areas (indicated in Table 2-9) fundamental to developing and testing a manned EVA system must be considered during the early stages of EVA system design and development. These support areas aid in optimizing the relationship of man to the mission operations and vehicle hardware. The purpose of this chapter is to identify the most important of these areas and to emphasize their importance by discussing their relation to total EVA system development and qualification.

The primary support areas that must be considered are as follows:

- Simulation/Training Hardware
- Simulation/Training Techniques
- Operational Procedures Development
- EVA Systems and Equipment Qualification/Acceptance Testing

4.1 DEVELOPMENT OF AN EVA SYSTEM

EVA system development is initiated when the requirement for EVA is established during the mission definition phase of a space program. Studies are conducted to identify gross crew functions required during the EVA. Analyses are then completed to define specific tasks (see Section 2.3) that must be performed. Simultaneously, EVA design guidelines and constraints, which are usually a function of vehicle design, are identified. When the tasks for mission performance have been analyzed, a complete description of hardware subsystems that must be integrated for EVA support can be determined. The remainder of EVA systems development focuses on integrating the tasks with the hardware subsystems to provide an EVA capability satisfying the mission objectives.

Figure 4-1 presents a first level overview of manned EVA system development. While providing a general outline of EVA system development, the overview identifies major support areas and outlines the chronological steps involved.

4.2 SIMULATION/TRAINING HARDWARE

The availability of simulation/training hardware is of primary importance in the development of a manned EVA system. Training hardware must be available to validate the man/system relationship and to familiarize the flight crew with the hardware and systems operations.

The hardware to be fabricated and its fidelity are defined by the level of simulations required and the stage of hardware development. In general, as design development progresses, so do the mockup fidelity requirements

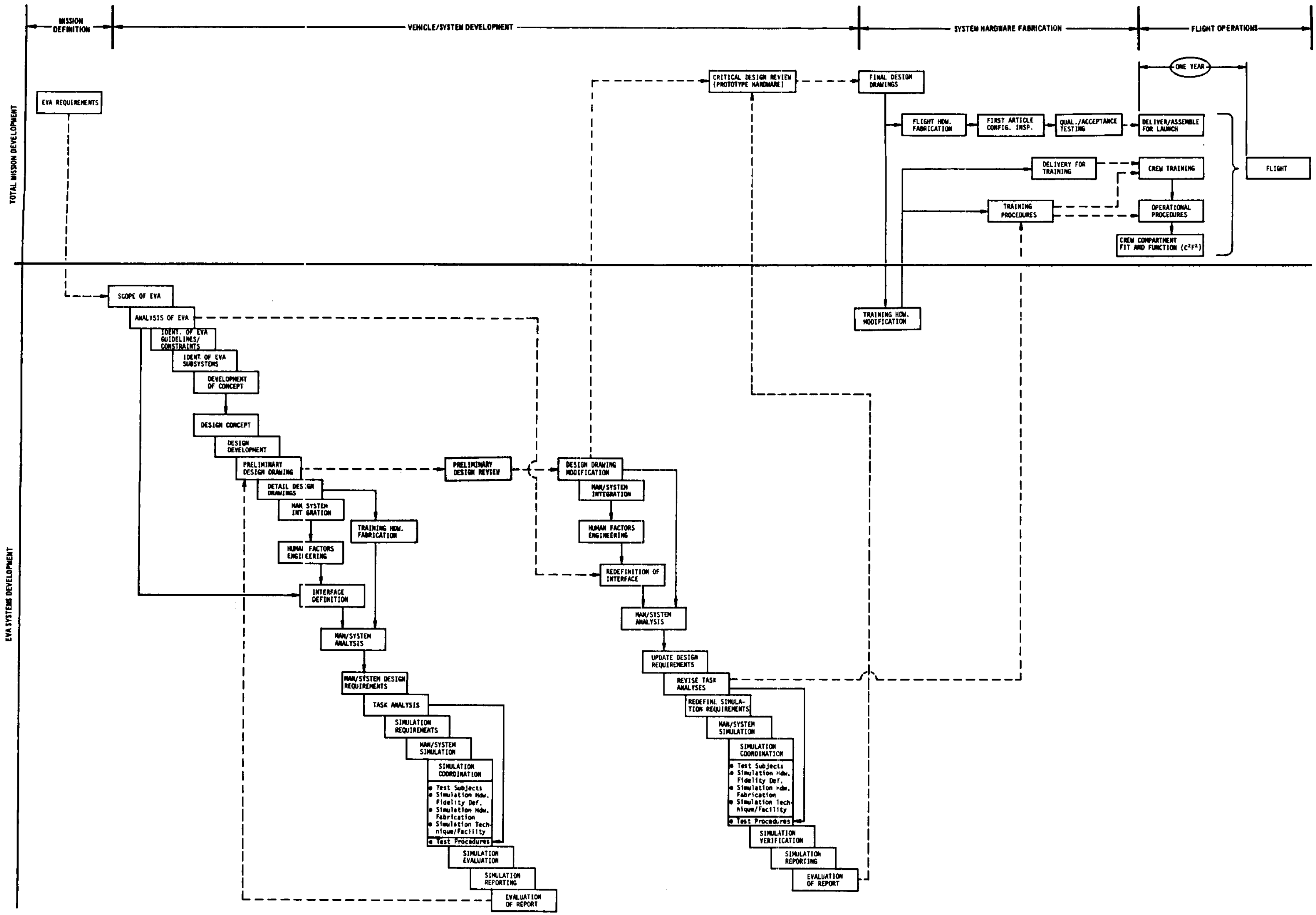


FIGURE 4-1: Development of an EVA System

(i.e., level of detail). In the early stages of design development, mockups of low fidelity are acceptable; but for verification simulations, high fidelity mockups are necessary. Also, variations in mockup fidelity are based on the choice of simulation technique. Developmental testing mockups are not required to be engineering hardware prototypes; they need only duplicate the prototypes in dimensional accuracies and functional operations.

The generally accepted simulation/training hardware fidelity definitions and an example of each are presented below.

- A - Flight Type: All functional and physical aspects of the component or subsystem will be representative of the flight design and will be operable and demonstrated within the appropriate environment. Example: Switch must turn on specific items of equipment as indicated on control panel.

- B - Functional Only: All functional aspects of the component or subsystem will be representative of flight design and will be operable and able to be demonstrated within the appropriate environment. Example: Switch must turn on specific items of equipment. Switch configuration will not represent flight hardware.

- C - Physical Only: All physical aspects of the component or subsystem will be representative of the flight design (installation and crew interfaces only) and will be operable and capable of demonstration within the appropriate environment. Example: Switch must operate functionally but does not need to operate other hardware.

- D - Envelope Only: Exterior shape of the component or subsystem will be representative of the flight design. In general, this hardware is used only to verify compartment location within the appropriate environment. Example: A switch on a control panel is not required to function; it must simply be painted on or shown in some fashion.

4.3 SIMULATION/TRAINING TECHNIQUES

4.3.1 Introduction

The area of simulation has achieved a high degree of importance in the development of manned spaceflight because of the need to accurately predict man's ability to perform in the space environment. Simulations provide the opportunity to identify, study, and resolve problems that evolve during man/system integration activities, to permit the selection of the most efficient systems, to enhance crew safety, and to increase the probability of mission success. Simulations also assist in achieving man/system compatibility by serving as the tools for evaluating candidate equipment. When the optimum combination has been developed, system verification programs are conducted using high fidelity mockups and realistic simulation environments. Astronaut training is then initiated in these same environments using prototypes of the flight hardware (modified only to accommodate the simulation

facilities). This permits the astronaut to become familiar with the operational characteristics of the hardware and equipment.

In this section, the simulation/training techniques that are normally selected for development and verification of orbital EVA systems/equipment are divided into two classes: (1) gravity-related and (2) atmosphere-related. Tables 4-1 and 4-2 list the location of representative water immersion and mechanical simulation facilities and include their associated characteristics and capabilities.

4.3.2 Gravity-Related Simulation/Training Techniques

As was evidenced during the early Gemini flights, the lack of a gravity environment during orbital EVA presented problems affecting the astronaut's ability to perform tasks and compromising mission success, since these problems were not completely identified and resolved in the design/development of the EVA system. During the later Gemini flights, reduced-gravity simulation became an area of increased concern as efforts were made to improve methods/techniques of simulating the zero-gravity environment to more effectively develop and evaluate the orbital man/system relationships.

The gravity-related simulation/training techniques generally recognized as suitable for development and evaluation of various man/hardware/task combinations are as follows:

- One-Gravity (1-g)
- Neutral Buoyancy (NB)
- Parabolic Flight (0-g)
- Multiple Degrees of Freedom (MDF)

When using these simulation techniques, certain operational parameters differ from those in the actual orbital (0-g) environment. Table 4-3 compares the effects of the different simulation techniques, using zero gravity as the baseline. The NASA Langley Research Center conducted a study to analyze the advantages of the available simulation techniques for specific classes of tasks. The results of the analyses are shown in Table 4-4. It is apparent from Tables 4-3 and 4-4 that each simulation technique possesses definite advantages and disadvantages. The techniques are compared in Table 4-5.

The following is a brief description of each technique, recognizing its unique characteristics and applications (refs. 4.1 and 4.2).

4.3.2.1 One-Gravity (1-g) Technique

One-g simulations, which employ standard earth gravity conditions, are an important tool in the development of orbital EVA systems. Past experience has established one-g simulations as a useful technique for defining and developing many of the man/hardware/task interfaces.

TABLE 4-1: Neutral Buoyancy/Water Immersion Facilities

ORGANIZATION LOCATION, & CONTACT	SHAPE	PHYSICAL DESCRIPTION								PHYSIOLOGICAL SYSTEMS							COMMUNICATION CAPABILITY				OBSERVATION CAPABILITY		PAST ACTIVITIES	REMARKS
		SIZE			ENVIRONMENT			RECOMPRESSION CHAMBER	CRANE CAPACITY	SUPPORT			MEASUREMENT				REAL TIME		TAPE RECORD		VIEWING PORTS	FILM CAMERA		
										BREATHING SYSTEMS			RESPIRATION RATE	EMG	HEART									
		LENGTH	WIDTH/DIA.	DEPTH	ENCLOSED	OPEN	WATER TEMP. CONTROL			SCUBA	HOOKAH	PRESS. SUIT			RATE	EKG	AUDIO	VIDEO	AUDIO	VIDEO				
Batelle Memorial Institute Columbus, Ohio Mr. Donald Frink	Rect. w/ att. cyl. (12' dia. x 33' dp)	15'	25'	12'	●		●	●		●			●		●	●	●		●	●		●	Hyperbaric testing of divers' hardware and hyperbaric chambers; animal research.	Not man-rated; full medical staff on hand.
Environmental Research Assoc. Essex, Maryland Mr. Lotes	Cyl.		20'	10'	●		●	●		●	●	●	●		●		●	●	●		●	●	Skylab IVA tests; study of crew/cargo restraints and mobility aids for advanced missions.	Computer-induced compensation for water drag in mass/cargo handling during zero-g simulations.
Garrett - AiResearch Los Angeles, Calif. Mr. Brent Green	Cyl.		20'	21'	●					●		●	●					●						No longer operational.
General Dynamics/Convair San Diego, Calif. Mr. Gary Thompson	Rect.	45'	35'	15'		●	●	●		●	●	●	●		●	●	●	●	●	●	●	●	EVA crew performance capability tests; IVA crew performance tests (Shuttle program only).	Full medical staff.
General Electric Valley Forge, Pa. Ms. Ruth Fry	Rect.	60'	28'	25'	●		●	●	4000 lb.	●		●	●		●	●	●	●	●	●		●	Training personnel for MOL and Tektite I & II programs; Apollo helmet distortion tests; blood transfusion during zero-g for IMBLMS; thermal pollution/underwater telemetry tests; M508 Apollo suit zero-g tests.	Full medical staff.
Lockheed Missiles & Space Sunnyvale, Calif. Mr. Syd Seidenstein	Cyl.		15'	12'	●		●			●		●	●	●	●	●	●	●	●	●	●	●	Skylab sun-end film retrieval tests; physiological test for effects of weightlessness.	Full medical staff.
LTV Astronautics Dallas, Texas	Cyl.	75'	30'	12'						●														No longer operational.
Marine Contractors Southport, Conn. Mr. William Duffy	Cyl.		12'	33'			●	●		●	●							●			●	●	Sealab tests.	
Martin Marietta Denver, Colorado Mr. Richard Skidmore	Cyl.		22'	16'	●		●	●	4000 lb.	●	●	●	●			●	●	●		●	●	●	Habitability design studies for future space missions.	Full medical staff.
McDonnell Douglas Huntington Beach, Calif. Mr. W. Woodward	Cyl.		30'	65'	●					●			●		●	●							Zero-g hardware qualification.	
McDonnell Douglas Santa Monica, Calif.	Rect.	50'	20'	16'						●		●												No longer operational.
NASA-LRC Hampton, Va.	Cyl.		40'	20'	●		●		1000 lb.	●	●	●	●					●		●	●	●	Mass handling and transfer evaluation tests (Handrail configuration, mobility aids, and tunnel configurations).	No longer operational.
NASA-MSC Houston, Texas Mr. Tony Smith	Cyl.		30'	16'	●		●	●		●		●	●				●	●	●	●	●	●	Various Skylab and Apollo tests.	
NASA-MSFC Huntsville, Ala. Mr. Jim Splawn	Cyl.		75'	45'	●		●	●		●	●	●			●		●	●	●	●	●	●	Evaluation tests and training for Skylab.	Zero-g manual force production test equipment available.
University of Calif. Los Angeles, Calif. Mr. Michael Willis	Cyl.		15'	15'		●	●			●			●		●	●	●		●		●		Cold water cognitive and physiological tests.	
USNADC Warminster, Pa. Mr. Bill Law	Cyl.		32'	30'		●	●	●	4500 lb.	●	●	●	●		●	●	●	●	●	●	●	●	Escape systems tests for U. S. Navy Aircraft (ejection seat egress, etc.).	Full medical staff.

TABLE 4-2: Multiple Degree of Freedom Simulator

SIMULATOR NAME, ORGANIZATION, LOCATION, & CONTACT	EXTENT OF FREE MOVEMENT					WEIGHT CAPACITY	MODE		GENERAL DESCRIPTION	PAST ACTIVITIES	REMARKS
	ROLL	PITCH	YAW	HORIZ.	VERT.		ZERO GRAVITY	PARTIAL GRAVITY			
Action-Reaction Free-Fall Simulator NASA, Huntsville, Ala. H. T. Blaise	360°	360°	360°	11' x 6'	6.5'	300 lbs.	●	●	Yoke with bearing-mounted harness; suspended from overhead air bearing pads. Vertical movement possible by negator springs; can be adjusted to simulate partial-g.	Astronaut training and activity evaluation; physiological parameter measurement during suited activity.	
Air Bearing Capture & Transfer Simulator NASA, Huntsville, Ala. H. T. Blaise	-	-	360°	58' x 24'	-	585 lbs.	●		Chair on platform supported by four air-bearing pads; attachable grappler.	Evaluation of a rate command grappling manipulator.	
Convair Six-Degrees-Of-Freedom Simulator, Air Bearing Space Simulator General Dynamics/Convair San Diego, Calif. Dr. Armstrong	360°	360°	360°	25' x 17'	4'	500 lbs.	●	●	Structure supported on four air pads on corners of an eight-foot square. Lower section supports two air bearing guides for the vertical tube, the top of which is fastened to the rotating gimbals. Human subject is supported in the gimbals with his CG coincident with the axes of rotation.	Evaluation of hatch and panel installation procedures in zero gravity; testing of personnel auxiliary maneuvering units; assembly tests for hardware.	Supporting six-degree-of-freedom workstation available.
EXSERP Serpentuator NASA, Huntsville, Ala. Mr. H. T. Blaise	±120° (at base)	±145° (free end)	±120° (at base)	40' radius		265 lbs.	●		Serpentuator has eight links, each with ±45° swing relative to adjacent link; has ±120° roll and ±120° yaw at base; has ±145° pitch and 360° roll capability on free end.	Support work for tooling concept for S-IV B Orbiting Workshop; remote manipulator studies.	Operator may be located on moving end of serpentuator. Serpentuator will possibly be adapted for use in a neutral buoyancy facility.
Five-Degrees-Of-Freedom Simulator NASA, Huntsville, Ala. H. T. Blaise	360°	±40°	360°		6.5'	215 lbs.	●		Yoke with bearing-mounted harness; rides above framework on air bearing pads.	Astronaut training and activity evaluation.	
Free Floating Simulator NASA-MSC Houston, Texas Mr. Lou Richards	360°	35°	360°	40' x 6'	17'	250 lbs.		●	Harness on gimbals.	Testing of EVA propulsion systems, evaluation and testing of ATM translation aids.	
INSERP Serpentuator NASA, Huntsville, Ala. Mr. H. T. Blaise	-	-	±180° (ea. link)	33' radius	-		●		Serpentuator has seven links, each with ±180° swing. Base roll and pitch capability to be added.	Support work for tooling concept for S-IV B Orbiting Workshop; remote manipulator studies.	Operated remotely. Will possibly be adapted for use in a neutral buoyancy facility.
Lunar Gravity Simulator Case Western Reserve University Cleveland, Ohio	180°	105°	360°		6'	265 lbs.		●	Subject suspended in harness from magnetic air bearings by cables.	Mobility studies in simulated lunar gravity.	No longer functional.
Lunar Gravity Simulator NASA, Langley Research Center Hampton, Va. Mr. Eric Stewart	0°	-	-	175'	-		●		Subject suspended on system of cables to walls on inclined plane.	Mobility studies in simulated lunar gravity.	Motion of body members is restricted to parallel planes.
LUNARG (Lunar Gravity Simulator) Lockheed Missiles & Space Sunnyvale, Calif. Dr. Syd Seidenstein	±90°	±90°	360°	18' x 36'	18'	250 lbs.		●	Consists of nine negator spring motors attached to a cable reeling system. Overhead rail system tracks test subject much like the movement of a pen on an x-y plotter.	Stress and performance studies on pressure-suited subjects in simulated lunar environment.	Treadmill available for lunar-g mobility studies.
Maneuvering Units Systems Test Laboratory (Frictionless Platform) LTV Astronautics Div. Dallas, Texas Mr. Ferguson	-	-	360°	40' dia.	-	490 lbs.	●		Chair on platform supported by four air-bearing pads; attachable grappler.	Evaluation of flight equipment and training of personnel for manned and unmanned remotely controlled space maneuvering units.	No longer functional.
Six-Degrees-of-Motion Simulator USAF, Wright-Patterson AFB Dayton, Ohio Mr. Chester May							●				No longer functional.
Space Operations Simulator Martin Marietta Denver, Colo. Mr. Paul Cramer	270°	270°	270°	60' dia.	40'		●	●	Servo-driven computer controlled, man-in-the-loop, movable bore system.	Evaluation of astronaut's ability to perform tasks in orbit; evaluation of tether dynamics; evaluation of maneuvering units.	Used in Skylab Experiment M507 design, verification, and crew training.
Spaceworker General Electric Valley Forge, Pa. Mr. Al Little							●				No longer functional.
ZEROG (Zero Gravity Simulator) Lockheed Missiles & Space Sunnyvale, Calif. Dr. Syd Seidenstein	360°	360°	360°	36' dia.	20'		●		Subject strapped into harness in large yoke; suspended from ceiling of high bay.	Developmental studies for ATM translation aids: handrails, etc.	

TABLE 4-3: Comparison of Zero Gravity Techniques

OPERATIONAL PARAMETERS	ENVIRONMENTAL SIMULATION TECHNIQUE			
	1-g	MDF	NB	0-g
Package Mass	Usually Light	Usually Light	Correct	Correct
Operator Strength/ Package Mass Ratio	Usually Greater	Usually Greater	Correct	Correct
Umbilical Handling	Incorrect (1-g effects)	Incorrect (1-g effects)	Usually Incorrect (Buoyancy effects)	Correct
Tether Usage	Correct while Attached	Correct while Attached	Correct while Attached	Correct
Vision	Correct	Correct	Correct	Correct
Lighting	Correct	Correct	Incorrect due to Dispersion in Water	Correct
Action/Reaction Forces	Incorrect	Limited	Correct	Correct
Latch Actuation Forces	Correct if Perpendicular to Gravity	Correct if Perpendicular to Gravity	Correct if Buoyant	Correct
Task Times	Usually Less	Usually Longer	Usually Less	Correct
Operator Body Stability	Partially Correct	Incorrect if Tethered or Attached to Task	Close to Correct	Correct
Translation (Operator & Package)	Incorrect	Incorrect if Tethered or Attached to Task	Correct if <1 ft/sec	Correct

The one-g technique is generally used for preliminary hardware evaluation and selection since mockups can be fabricated inexpensively and from a variety of materials. The technique, which is readily adaptable to both shirtsleeve and pressure suited conditions, is useful for developing and evaluating fixed position worksites where no gross body movements are required. The technique is also very valuable in conducting Crew Station Reviews (CSR) and Critical Design Reviews (CDR) of the total spacecraft systems.

As a training technique, one-g is used to familiarize the flight crews with the EVA hardware and hardware/spacecraft interfaces and also to develop operational procedures. The one-g technique is the most valuable and, in many cases, the only method for evaluating/verifying certain spacecraft systems such as electrical control panels, solar panel deployment, total spacecraft systems, etc.

TABLE 4-4: Simulation Technique Comparison

TECHNIQUE CONSIDERATIONS	SIMULATION/TRAINING TECHNIQUE			
	1-g	MDF	NB	0-g
Six Degrees of Freedom		●	●	●
Long Duration Testing	●	●	●	
Unrestricted Body Motion			●	●
Stable Reference Frame	●	●	●	
No Data Bias From Anxiety	●	●	●	
Low Drag or Friction Effects		●		●
Luggage Handling Capabilities			●	●
Large Masses Accomodated		●	●	
Delicate Equipment Handling	●	●	●	
Valid Propulsion Testing		●		
Stability System Tests Possible		●		●

4.3.2.2 Neutral Buoyancy (NB) Technique

The technique of simulating zero gravity (weightlessness) by immersing man in water has unique features. Weight and balance techniques have been worked out to achieve neutral buoyancy in all planes, permitting the neutrally buoyant subject to operate in six degrees of freedom for long periods of time unrestrained by connecting lines, counterbalancing masses, yokes, or gimbal systems. This simulation technique provides total support of the body appendages and is relatively insensitive to changes in center of gravity. It is not time-limited, and an entire set of extravehicular procedures can be evaluated without interruption.

The neutral buoyancy technique was initially adapted to solving problems associated with EVA following the Gemini IX-A flight. The technique was improved and expanded through Gemini X and XI and fully utilized in evaluating the Gemini XII EVA tasks, equipment, and timelines, and in training the Gemini XII prime and backup EVA pilots. It was concluded that neutral buoyancy simulation and training contributed materially to the success of the Gemini XII EVA. The post-mission evaluations indicated that there was a good correlation between the underwater simulation and the actual EVA weightless conditions in orbit, that is, there was strong evidence that tasks which were readily

TABLE 4-5: Simulation Techniques Advantages and Disadvantages

SIMULATION TECHNIQUE	ADVANTAGES	DISADVANTAGES
PARABOLIC FLIGHT	● Nullifies the gravitational body forces with inertial body forces. ● Relative freedom of motion (6 degrees of freedom without restraining framework or liquid-imposed drag). ● Excellent for (1) development/verification of design and procedures using hi-fi mockups, (2) development requirements for crew translation and restraint aids. ● Suitable for obtaining hard wire quantitative measurements.	● Highly trained personnel required to pilot and maintain aircraft. ● Relatively weather dependent. ● Limited volume with aircraft (60' long x 10-1/2' wide x 6-1/2' high). ● Special modifications required for any research aircraft to be flown at 0-g. ● High incidence of motion sickness. ● Shortness of low-gravity periods (15-30 sec./parabola) and accompanying high-gravity periods. ● Test procedures must take into account the limited duration of 0-g. ● Crew safety during pull-ups and pull-outs. ● Heavy equipment attached to the aircraft picks up buffeting and may perturb zero-g operations when the subject interacts with it.
NEUTRAL BUOYANCY	● Permits operation in 6 degrees of freedom for long periods of time, unrestrained by connecting lines, counterbalancing masses, yokes or gimbal systems. ● Total support of body appendages. ● Relatively insensitive to changes in center of gravity. ● An entire set of EVA procedures can be completed without interruption. ● Controllable environmental conditions.	● Drag and damping effects. ● Necessity for added mass due to ballast requirements. ● Attitude stability characteristics imposed by water depth/pressure relationships and non-rigid suit. ● Reduction in capability to obtain quantitative real-time measurements due to water related problems.
ONE GRAVITY/ MULTIPLE DEGREES OF FREEDOM (MDF)	● Useful tools in developing workstations that require limited gross body movements. ● Evolution of early design concepts through use of low fidelity mockups. ● Useful in Critical Design Review (CDR) walkthroughs. ● Useful tool for timeline development. ● Useful tool for lighting system development.	● Does not remove any psychosensory cues. ● Does not permit entire cluster mockup to be presented in the orbital assembly.

accomplished underwater were also accomplished readily in orbit. This technique is currently being used in the Apollo and Skylab Programs for systems verification and crew training.

Neutral buoyancy simulation/training has been applied to extravehicular activities which require gross body movements. These include ingress/egress, translation, rescue, crew and cargo transfer, maintenance and assembly, and the development of operational procedures. This technique, which is generally not time dependent, is therefore very suitable for studying task integration and long duration mission-related tasks. If the simulation/training facility is of sufficient size, an entire EVA operation from spacecraft egress, through task completion, to spacecraft ingress can be conducted. It should be pointed out that the design and fabrication of mockups for use in a water environment requires specialized fabrication methods and materials. Therefore, this technique is not particularly suited to early design development. It is better used, instead, as a means of evaluation and verification of specific systems following initial concept approval.

4.3.2.3 Parabolic Flight (0-g) Technique

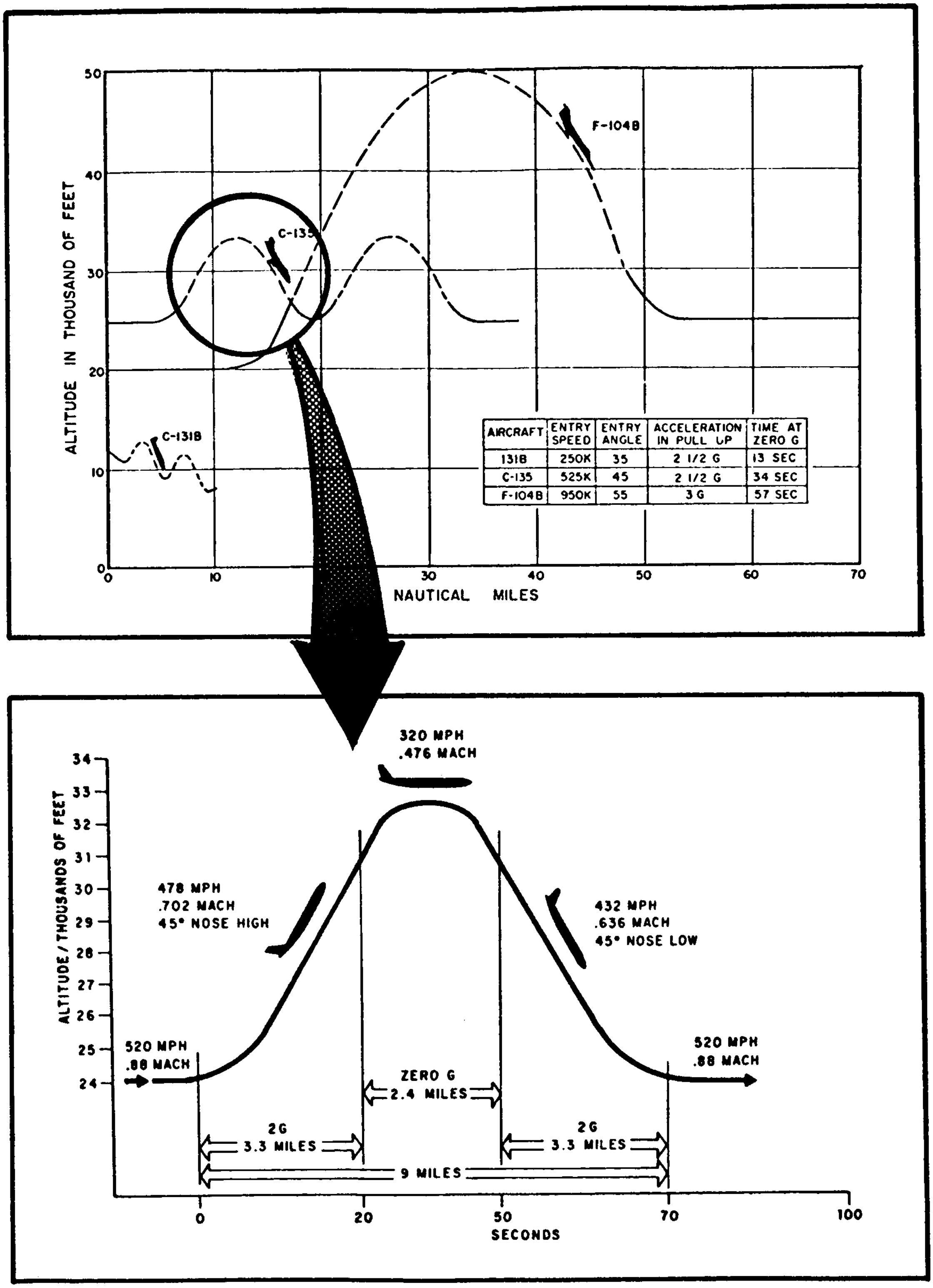
The parabolic flight technique is presently used to validate system designs, equipment interfaces, flight procedures, and provide crew training for the phases of an EVA mission that can be adequately simulated within the aircraft facility and operational constraints. It is the only technique that produces a true simulation of zero-gravity. The parabolic flight technique consists of having a specially equipped aircraft fly Keplerian trajectories. This maneuver places the aircraft and its inhabitants in a controlled state of free fall. By repeatedly flying the parabolic maneuvers, several periods of weightlessness for up to 57 seconds can be experienced using the F-104B aircraft. Presently, a modified Air Force KC-135 aircraft is used by NASA for this simulation/training activity.

As indicated in Figure 4-2, an increase in the gravitational force is experienced during pull-up and pull-out maneuvers. The increased gravity level is normally two to two and one half times normal earth gravity. The KC-135 aircraft produces periods of weightlessness up to 30 seconds duration and periods of increased gravity of up to 20 seconds. The degree of zero gravity accuracy is ±0.01g and depends primarily upon prevailing weather conditions.

Guidelines and constraints for performing simulation/evaluation programs using the parabolic flight techniques and equipment are contained in Appendix C.

4.3.2.4 Multiple Degrees of Freedom (MDF)

The multiple degree of freedom simulation technique (which involves hardware such as sling suspension/gimbals, air pads, air bearings and spring combinations) is useful in the development of EVA capability, since it provides an approximation of the reaction forces that occur in a zero gravity environment. This technique provides a useful tool for developing fixed position, standup or sitdown workstations (independent of orientation in the payload application) that require limited gross body movements. The



AIRCRAFT	ENTRY SPEED	ENTRY ANGLE	ACCELERATION IN PULL UP	TIME AT ZERO G
131B	250K	35	2 1/2 G	13 SEC
C-135	525K	45	2 1/2 G	34 SEC
F-104B	950K	55	3 G	57 SEC

FIGURE 4-2: Parabolic Flight (0-g) Technique

technique, which can provide from one to six degrees of freedom, lends itself to the evolution of early design concepts through use of low fidelity mockups.

This technique provides an acceptable means of developing and evaluating maneuvering unit (AMU, HHMU, etc.) operational procedures and crew training. During the Gemini Program, maneuvering unit training exercises were conducted on an air-bearing platform. The simulation provided three of the six degrees of freedom experienced in the weightless environment and familiarized the crews with the handling characteristics of each unit. However, only one angular degree of freedom could be simulated at a time. Sling and gimbal systems were also used for training exercises in which the EVA crewman was suspended above a mockup for special task evaluations. This type of simulation (four-degrees-of-freedom) introduced the crew to problems associated with the performance of tasks in a weightless condition.

4.3.3 Atmosphere-Related Simulation/Training Techniques

In addition to the gravity-related simulation/training techniques, there are several atmosphere-related techniques that are used to develop EVA hardware and to train EVA crew members. The technique includes thermal/vacuum chamber testing. This type of testing is a fundamental phase of space suit, life support, and spacecraft pressurization system development, evaluation and verification.

As an EVA training technique, the thermal/vacuum chamber training provides familiarization for flight crews in a simulated space environment. Each crewman performs simulated EVA missions in the chambers using the actual spacecraft. The training exercises include checkout and donning of the primary and secondary life support systems. These tests familiarize the crew with the EVA systems operations under thermal/vacuum conditions and provide increased confidence in the equipment to be used in flight.

4.4 OPERATIONAL PROCEDURES REQUIREMENTS

4.4.1 Introduction

The planning and development of an orbital EVA mission, like the development of spacecraft hardware or crewman support systems, proceeds from previously specified objectives and becomes constrained by system characteristics and operational considerations. Basically, the development process for operating procedures to support an EVA mission consists of a series of iterative cycles where a procedure is defined to increasingly finer levels of detail as the total program progresses and flight hardware and operational considerations become better known. As the spacecraft hardware and crewman support equipment designs solidify, the procedures are limited by the capabilities of the vehicle support systems, ground support facilities and flight software. The final procedures development phase normally occurs during the year prior to launch (see Figure 4-1) and involves detailed flight procedures, techniques, and mission rules to be used by the flight crew and ground control personnel for both nominal and contingency missions.

The mission planner and designer must recognize that the familiarization, evaluation, and flight tests for verifying hardware design, hardware/crew

performance and operational techniques will require considerable procedures development activity. The development of high fidelity procedures for crew training and, finally, inflight operational procedures will require special and detailed consideration to assure crew safety and total mission success.

4.4.2 EVA Procedures Development and Verification

The scope and complexity of manned extravehicular activities necessitates broad operational procedures development and verification programs. The many functions that must be performed by the crew throughout each mission require a variety of part-task and total mission simulations to ensure proficiency in systems and experiment operations. Of particular interest in this document are the procedures development and verification requirements necessary to support manned extravehicular operations. The quantity of procedures required during EVA systems development and crew training programs and the timely integration of the operational procedures into the total mission profile are of major importance. Detailed procedures for the operation of on-orbit EVA equipment, EVA preparation, EVA task performance, and post-EVA operations normally result from integrating a series of test procedures and task analyses developed from early crew familiarization, indoctrination, and training activities.

4.4.2.1 Test Procedures

Test procedures are required early in the EVA hardware and support system testing programs to provide a methodology for equipment operation, for man/system interface evaluation, and for verification of the operational characteristics of the EVA hardware when subjected to a simulated orbital space environment. The test procedures provide a format compatible with the particular simulation facility and the equipment that supports the test. The test may range from simple "bench" checks to hardware verification conducted in a thermal-vacuum chamber. The test procedures generally include the following:

- Test objectives
- Test design
- Test facilities and equipment
- Independent, dependent and control measures
- Sequential operations procedures
- Equipment design details to be investigated
- Test subject training requirements
- Test subject number and size
- Test report requirements

4.4.2.2 Task Analyses

Task analyses are generated to serve as guides for the operation of hardware and crew support equipment, preliminary timeline development, and initial crew training. Task analyses development is initiated following the

establishment of the man-missions interface definitions and may parallel test procedures development. The initial task analyses usually provide an early look at task performance capabilities and techniques for certain areas of the EVA mission and are refined, as high fidelity hardware becomes available, to include end-to-end EVA operations. The task analyses are updated throughout the later phases of the mission hardware development program and can frequently be used to aid in the preparation of training procedures, operational procedures, and mission profiles. An example of an EVA task analysis format is shown in Figure 4-3 (ref. 4.3).

4.4.2.3 Training Procedures

Training procedures are developed for EVA operations to provide actual practice of the skills and techniques required to operate the EVA systems and perform the EVA tasks under both nominal and contingency conditions. The training allows the crewman to become proficient in the performance of each EVA function through his participation in the various simulator test programs and in specific training exercises. Training procedures are required for each EVA operation, including the following EVA associated functions:

- Space suit donning, doffing, and operation
- Life support system operations and limitations
- Airlock depressurization/repressurization
- Egress hatch operations (also interior hatches)
- EVA experiment/hardware operation
- Crew and cargo transfer
- Contingency operations and rescue

4.4.2.4 Operational Procedures

Operational procedures are developed for inflight application, and they provide a detailed description of the crew assignments and their operational sequence throughout the mission profile. The procedures are usually developed from iterative cycles of the task analyses and training procedures and will have been verified through earth-gravity simulation, altitude-chamber tests, and reduced (or zero) gravity simulations. A typical page from the Apollo 15 lunar surface EVA (No.1) operational procedures is shown in Figure 4-4. The Commander (CDR) and Lunar Module Pilot (LMP) checklists, worn on the space suit cuff, are shown in Figure 4-5 for the same time frame (ref. 4.4) Mission flight plans can be developed from verified inflight operational procedures. A typical flight plan for the Apollo 16 transearth EVA is shown in Figure 4-6 (ref. 4.5).

4.5. EVA SYSTEMS AND EQUIPMENT QUALIFICATION/ACCEPTANCE TESTING

4.5.1 Introduction

As indicated in Section 4.1, one of the final steps in system development is that of flight hardware qualification/acceptance testing. The purpose of

TASK ANALYSIS **APOLLO APPLICATIONS PROGRAM**

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVAL
A			

ACTIVITY CODE AND TITLE: D021 - Expandable Airlock Technology FLIGHT NO.: AAP-2/AAP-3 DATE: 9 January 1970 ANALYST: Thomas

TIME: (min) Cum	1	2	3	G	FUNCTION AND CREW TASK/EVENT	CREW STA	OPERATING ENVIRONMENT	ENERGY RATE BTU/HR	SKILL NOTE	CONTROL	DISPLAY	OTHER EQUIPMENT	REF DOC/ DWG NO.	DE-SIGN NOTE	REMARKS/NOTES
					5.0 <u>PERFORM EXPERIMENT EVA TEST AND FIRST D021/D024 SAMPLE RETRIEVAL</u>		Pressurized Suit								5.0 NOTE: Function 5.0 immediately follows Function 4.0.
	5.0	5.0			5.1 Depressurize AM.	6	"	1500							5.1 NOTE: AM depressurization time is estimated to be 5 mins.
		5.0			5.2 During steps 5.3 and 5.4, act as safety observer and manage 16mm Camera Power Cable and Crewman 1's suit umbilical.	6	"	3000							
	2.0				5.3 Open AM EVA hatch.	6	"	3000							
	3.0				5.4 Egress EVA hatch and stabilize.	6-8	"	3000							
	(1.0)	1.0			5.5 Close AM vent valve.	6	"	3000							
		.2			5.6 During step 5.7, act as safety observer and manage 16mm Camera Power Cable and Crewman 1's suit umbilical.	6	"	3000							
	.2				5.7 Translate to D021 EVA translation aid device and stabilize. (Wait for Crewman 2 during step 5.8).	8	"	3000							5.7 NOTES: 1) EVA translation rate is estimated to be .5 ft. per second; 2) It is assumed that translation aids will be provided for getting to the Expandable Airlock hatch and the 16mm camera mounting locations. It is suggested that a dual rail system similar to that now proposed for the ATM Sun End film retrieval be employed for getting to the D021 hatch. It would also help if the dual rail device could be used for the D021/D024 sample retrievals.
	(3.3)	3.3			5.8 Egress AM EVA hatch, translate to the EVA workstation outside the AM EVA hatch, stabilize and restrain.	6-8	"	3000							
		31.8			5.9 During steps 5.10 thru 5.45, act as safety observer and manage 16mm camera power cable and Crewman 1's suit umbilical.	8	"	3000							
	1.0				5.10 Translate to first 16mm camera mounting location <u>TBD</u>; stabilize and restrain.	8-9	"	3000							5.10 NOTES: 1) EVA translation rate is estimated to be .5 ft. per second; 2) 16mm camera mounting location is <u>TBD</u>; 3) translation route is <u>TBD</u>, but is estimated to be a maximum of 30 feet
	1.0				5.11 Detach 16mm camera from pressure suit restraint and mount 16mm camera at its mounting location.	9	"	2500							
	.5				5.12 Aim 16mm camera toward Expandable Airlock hatch.	9	"	2500							

SHEET

FIGURE 4-3: Typical EVA Task Analysis Format

MISSION: APOLLO 15 DATE: 4/22/71
EVA: 1

LMP ACTIVITIES	EVA TIME	CDR ACTIVITIES	SEQ CAM	TASK FUNCTION LMP	TASK FUNCTION CDR
Assist CDR	0+10	Move through hatch			
Deploy CDR PLSS antenna		Deploy PLSS antenna			
Place jettison bag in hatch		Descend ladder to deploy MESA			
Remove LEC, loop end, from stowage bag		Deploy MESA Retrieve & discard jettison bag into Quad I			
Pass LEC, loop end, to CDR		Deploy LEC			
		Descend ladder to surface			
Verify CB configuration		Check footing, stability, and mobility			
Attach LEC to overhead handhold		Kick jettison bag under LM			
Transfer ETB to surface	0+20	Transfer ETB to surface			
Remove from handhold & stow LEC		Hang ETB on LEC stowage hook			
Move through hatch		Adjust MESA height			
Close hatch		Loosen MESA blanket around TV camera			
Descend to surface		Open MESA blankets			
Deploy PLSS antenna		Deploy LMP PLSS antenna			
Check footing, stability, and mobility		Unstow, deploy, and place TV tripod on surface			
		Unstow and mount TV camera on tripod			
Remove CSC from pocket		Pass TV camera under +Z foot pad			
Deploy CSC handle & bag Collect contingency sample		Position TV at 12:00/50' to view Quads I & IV			
Remove handle & close bag					
Climb LM ladder & place cont sample on platform	0+30	Deploy left LRV offload tape across secondary strut			

STC/LPD-0681 NASA—MSC

FIGURE 4-4: Typical Lunar Surface Operational Procedures Format (Apollo 15 EVA)

this section is (1) to provide a brief overview of the scope and nature of qualification/acceptance testing; (2) to present several of the recommendations that have been generated during the past ten years of qualification/acceptance testing; and (3) to provide a representative example of the types of qualification/acceptance tests to which flight hardware might be subjected.

CDR-1 EVA-1 4/19/71

CDR EVA 1

0+10 Move Through Hatch
PLSS Antenna - Deploy
MESA - Deploy
Jett Bag - Discard
LEC - Deploy

Descend to Surface
FAM
Jett Bag - Under LM

0+20 ETB - Transfer Down

MESA Height - Adjust
Blankets - Remove
TV Tripod - Unstow
TV Camera - to Tripod
TV - Position 12:00/50 FT
Lens - Set F-TBD

COMMANDER (CDR)

LMP-1 EVA-1 4/19/71

LMP EVA 1

0+10 Assist CDR Egress
CDR PLSS Antenna - Deploy
Jett Bag - Place in Hatch
LEC - to CDR

CB Configuration - Verify

LEC to Overhead Handhold
0+20 ETB - Transfer
LEC - Stow

Egress
Hatch - Close
Descend to Surface

FAM - PLSS Antenna Unstow

Contingency Sample - Collect

LUNAR MODULE PILOT (LMP)

FIGURE 4-5: Crew EVA Cuff Checklist

4.5.2 Nature and Scope of Qualification/Acceptance Testing

The test program should be designed to evaluate all aspects of the performance capability of the system and its elements under simulated nominal values and combinations of extremes in anticipated mission conditions. Testing should be directed toward the following:

- Verifying capability of the design.
- Evaluating the susceptibility of the design and the hardware to failures, either through known failure modes and mechanisms or through those which had not previously been revealed in design reviews or reliability analyses.
- Identifying unexpected interactions among components.
- Identifying failure modes which reflect deficiencies in materials, workmanship or quality control.

Tests should be planned using statistical design-of-experiment techniques, wherever the cost is practical, and should be conducted under environmental stress levels and time periods appropriate to the purpose of the test. Test and launch support equipment should have been acceptance tested prior to use.

All elements of the system hardware in their mission configuration should be qualified at appropriate levels of assembly to ensure the capability of each design to perform its intended functions under mission conditions. Qualification requirements should be established on the basis of anticipated mission requirements local to each item of the hardware being qualified. Levels of overstress, appropriate for each environmental and performance parameter, should be selected to characterize the capability of the hardware

FLIGHT PLAN

MCC-H	1503 CST			NOTES
	243:00 (10001) (10011)	MSFN	CMP DON EVA EQUIPMENT	SIM EXP STATUS (*0000) (00000)
	:10		CDR/LMP INTEGRITY CHECK	
			CMP INTEGRITY CHECK	
UPDATE TO CSM GO/NO-GO FOR CABIN DEPRESS	:20		GO/NO-GO FOR CABIN DEPRESS	
			CABIN DEPRESS	
			HATCH OPENING	
	243:30		CMP EGRESS	
			FAMILIARIZATION	
	:40	TV	INSTALL TV/DAC, ADJUST	
			RETRIEVE PAN CAMERA CASSETTE	
	:50			
			REST	
			RETRIEVE MAPPING CAMERA CASSETTE	
	244:00 (10001) (10011)	TV		
			REST	
		MSFN	REMOVE TV/DAC & DEPLOY MEED	
	:10		PHOTOGRAPH MEED	
			EXPOSE MEED FOR 10 MINUTES	
	:20			CSM EVA LENGTH ___ HR MAX
			CLOSE MEED	
			REMOVE MEED	
	244:30			
			INGRESS	
	:40		HATCH CLOSING	
			CABIN REPRESS	
	:50			
			OPS DEPLETION	
	245:00		CONCLUDE CABIN REPRESS	

MISSION	EDITION	DATE	TIME	DAY/REV	PAGE
APOLLO 16	PRELIM (3/17)	12/6/71	244:00 - 245:00	11/TEC	3-353

FIGURE 4-6: Flight Plan for Apollo Transearth EVA

item being qualified. Levels of development at which qualification testing may be required are as follows: parts, devices, and materials; components; subsystems; and systems (ref. 4.6).

4.5.3 Qualification/Acceptance Testing Recommendations

In retrospect, several recommendations and points of interest stand out from the test experience gained over the past ten years during three major manned spacecraft programs: Mercury, Gemini, and Apollo. The recommendations and points of interest are indicated below (ref. 4.7):

- Design and development testing plays an important part in the overall test plan. Perform it as early as possible. Document the results well, and hold the data for future reference. Pay particular attention to what seem to be minor details, especially for substitute parts and "explained" failures.

- Allow development testing completion to be a constraint on critical design.

- Perform qualification testing at the highest possible level of assembly practical within reasonable cost and schedule constraints.

- Before subjecting qualification test specimens to qualification test levels, acceptance test the specimens by following approved test procedures under strict change control. Include applicable environmental acceptance tests.

- Qualification test specimens must come from among normal production items manufactured and assembled using final blueprints and processes under normal quality control and with production tooling and handling fixtures.

- Make qualification tests rigorous and complete, yet realistic. A strong tendency exists to qualify equipment to the designer's desires rather than to the actual requirements. Where flight equipment will never leave controlled cleanroom conditions and need operate only in outer space after launch, take care not to fall into the classical qualification test programs, which require such things as salt-water immersion, rain and dust, cyclic humidity, fungus, and other environmental extremes.

- Carefully document, track, explain, and take necessary corrective action on test failures encountered on all production hardware. Qualification test hardware, by definition and from bitter experience, must count as production hardware. No suspected failure encountered during any test on production hardware should escape from this rule, no matter how insignificant or unrelated the failure may seem at the time. Experience has shown that major failures always receive adequate attention. The minor unreported failure is the one that slips by and shows up later in the vehicle test cycle or, worst of all, in flight.

- Close out all failures of nonflight training hardware when the failure occurs on flight type controls, connections, etc. Too often design deficiencies and poor wear are "invited" by ascribing failures to overstress.

- Perform qualification vibration testing at excitation levels that provide an appropriate margin of safety over the expected environments, including acceptance vibration testing. Because of weight and volume considerations, power consumption, or other limiting factors, this margin may have to decrease. When this becomes evident, treat each case on an individual basis and make sure all parties involved understand.

- Thermal test for qualification to temperature limits at least 20° F outside the expected temperature limits, including acceptance thermal testing. (The temperature "limits" may need to be varied for certain cases.)

- Monitor the functioning of test specimens during the dynamic phases of qualification and environmental acceptance testing as completely as possible. Test all functions with 100-percent monitoring, including all redundant paths, before and after appropriate phases of the qualification and acceptance tests.

- When a complete, deliverable item of critical mechanical or electrical equipment cannot be visually inspected or functionally tested (or both) for design, manufacturing, assembly, handling, and procedural/workmanship errors, subject the components of this equipment to environmental acceptance tests.

- Determine environmental acceptance test requirements on an individual basis, considering what types and what levels of tests reveal quality or workmanship defects. Examine the failure history of each component during the engineering and development stages and during qualification testing. Look at the failure history of like components using similar manufacturing and assembly techniques, particularly those made by the same vendor, in the same plant, and by the same people.

- Carry out environmental acceptance testing at the lowest practical level of assembly. For example, it is much better to find the solder balls in a sealed relay before building it into an assembly than to cope with an intermittent system failure on the launch pad. The earlier one uncovers a problem and eliminates it from downstream hardware, the less its impact on the overall program.

- Carefully examine changes of any nature to the hardware for their effect on qualification and acceptance test results. Qualification by similarity can give very misleading results and should take place only with full knowledge of all parties concerned. In the case of acceptance testing, the simple act of removing a cover plate for inspection purposes constitutes potential grounds for a reacceptance test.

- Total vehicle environmental acceptance tests are desirable. However, tests of this nature become virtually impossible to perform on manned spacecraft. Thorough qualification of spacecraft components, including wiring and tubing installations, combined with proper environmental acceptance tests of the equipment before installation, has, thus far, assured mission success.

- Always retest after changes to the hardware or software have been made. Set up rigorous controls to assure that this is done.

- When possible, test all functions and paths on the installed systems at least once prior to delivery to the launch site. As a general rule, when changes or replacements require retesting, do it at the factory. Prelaunch testing at the launch site should demonstrate total space-vehicle and launch-complex compatibility and readiness. They should not simply prove the adequacy of a given component or of a single system.

- At the start of a program, devise a thorough overall integrated test plan that includes all testing (including engineering and development, qualification, reliability and life, predelivery environmental acceptance, preinstallation acceptance, installed system, altitude, prelaunch, and early unmanned flight test). The plan should include as much testing as necessary to gain confidence in the hardware, the software, the test equipment, the test procedures, the launch procedures, and the flight crew procedures. The plan should provide for deleting unnecessary phases of testing as confidence grows.

4.5.4 Representative Example of System Qualification/Acceptance Testing

The following is a brief description of the types of tests used in qualifying a Space Suit System and its associated support equipment. The information was derived from several Master End Item Specifications (refs. 4.8 and 4.9).

- Design Limit Cycling: This type of test subjects the Contract End Item (CEI) to cycling operations while being worn under laboratory ambient conditions. Condition requirements are defined by NASA and are representative of those to be encountered during actual use.

- Design Limit Environments: This type of testing is conducted at both the CEI and materials level. The environmental tests required at each level are shown in the chart on the following page.

- Mission Interface Tests: The mission interface tests subject the CEI to the following, in order to demonstrate proper physical and performance interfaces:

  - Spacecraft
  - Extravehicular Activity
  - Electromagnetic Radiation and Acoustic Noise
  - Total Extravehicular Mobility Unit (EMU) Interface

CONTRACT END ITEM QUALIFICATION/ACCEPTANCE TESTS	MATERIALS LEVEL QUALIFICATION/ACCEPTANCE TESTS
Humidity	Fungus
Oxygen	Combustion
Salt	Urine Compatibility
Fog	Toxicity (Out-gassing)
Sand and Dust	Ignition Proof
Stowage: Hi/Lo Temp.	Feces Compatibility
Vibration	
Impact Shock	
Acceleration	
Salt Water Immersion	
Pressure Integrity	
Acoustics	

REFERENCE

4.1 Carl Larson. "Man/System Simulation", NASA Internal Note IN-ASTN-S-69-3, March 1969.

4.2 "Reduced Gravity Simulation", Special Edition, Human Factors Journal Volume 11, No. 5, October 1969.

4.3 NASA: "D020 Expandable Airlock Technology", Task Analysis, January 9, 1970.

4.4 Manned Spacedraft Center: Preliminary Lunar Surface Procedures -- Apollo 15, MSC Crew Systems Division, Houston, Tex., April 1971.

4.5 Manned Spacecraft Center: Preliminary Flight Plan -- Apollo 15, MSC Crew Procedures Division, Houston, Tex., December 1971.

4.6 NASA: Reliability Program Provisions for Aeronautical and Space System Contractors, NHB 5300.4 (1A), Washington, D.C., April 1970, pp. 4-2 through 4-3.

4.7 NASA: What Made Apollo a Success? NASA-SP-287, Washington, D.C., 1971.

4.8 Manned Spacecraft Center: Extravehicular Mobility Unit for Lunar Module Crewmen (EMU/LM), Apollo J-Missions, Master End Item Specification Performance/Design and Product Configuration Requirements, CSD-A-1059, Houston, Tex., August 31, 1971.

4.9 Manned Spacecraft Center: Skylab Extravehicular Mobility Unit, Master End Item Specification Performance and Design Requirements, MSC-020806, Houston, Tex., October 6, 1971.

CHAPTER V

ORBITAL EVA HUMAN PERFORMANCE AND BIOMEDICAL CHARACTERISTICS

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

SECTION PAGE

5.0 INTRODUCTION

Man's ability to conduct orbital EVA tasks is a function of his physical and physiological performance in the extravehicular environment. Physical performance, in this context, refers to the types of tasks he is capable of performing, the forces he can exert, the distances he can reach, etc. His physiological performance refers to the biomedical condition of the crewman during EVA; parameters such as heart rate, energy expenditure, body temperature, etc. are vital indicators of the crewman's physiological condition.

Very limited data are available concerning the performance capabilities of man in an orbital or transearth EV environment. Currently extant material relevant to performance comes mainly from the orbital EVA that was performed on five of the Gemini missions and on the Apollo 9 mission, and the transearth EVA that was performed on the later Apollo missions.

Up to and including the Apollo 16 mission, approximately eight (8) hours were logged relating the performance of mission tasks accomplished completely outside the spacecraft. Another 6.24 hours of EVA performance while standing in the open hatch were logged. Much of the total extravehicular time was spent evaluating advanced support equipment, retrieving experimental packages and conducting photographic experiments. The performance of these EVA tasks, along with ground based studies, has provided valuable information, although the available data are still considered too sparce for the formulation of a valid set of EVA performance characteristics. Section 5.1 of this chapter presents available crew performance data derived primarily from mission reports on the Gemini and Apollo programs and from ground based studies.

The biomedical/physiological characteristics presented in Section 5.2 are concerned with (1) the safety and comfort of the extravehicular crewman, (2) the environmental parameters necessitating biomedical/physiological monitoring, (3) the parameters monitored during EVA, and (4) a description of the methods and equipment used in monitoring certain parameters.

5.1 PERFORMANCE CHARACTERISTICS

Man's performance capabilities in the gravity free, orbital EVA environment are highly dependent upon the mobility aids, restraint equipment, transfer systems (crew and cargo) and worksite provisions (lighting, tools, controls and displays) available to accomplish a specific task. In addition to the restrictions imposed by support hardware, performance is also limited by space suit mobility restrictions, task sequence, and workload control. One means for presenting information on performance capabilities is a description of the major operations required by the crewman during an orbital EVA mission. These major EVA operations include: ingress/egress, translation, and worksite activities. Subcategories within these operations are listed on the following page:

- Ingress/Egress
  - hatches
    - (a) man
    - (b) cargo
  - worksites
    - (a) man
    - (b) cargo
- Worksite Activities
  - body position control
  - task performance
- Translation
  - man unaided
  - man aided
  - man/cargo unaided
  - man/cargo aided

5.1.1 Ingress/Egress

The EVA performance capability requirements associated with ingress/egress operations include the crewman's ability, with the proper supporting hardware, to control body position and movement during passage through confined openings such as hatches and spacecraft structures and during entrance into or exit from an EVA worksite. The astronaut may be required to manually transport cargo through hatches or to and from the worksites. In order to provide the most useful equipment for crewman ingress/egress activities, the EVA mission planners and hardware designers require information such as the time required for ingress or egress, the difficulty involved in body positioning, the difficulty of cargo transfer, and the hatch/worksite accessibility requirements. The discussion below presents data available from past missions and ground based tests which are related to each of these areas. Hatch ingress/egress and worksite ingress/egress are discussed separately.

5.1.1.1 Hatch Ingress/Egress

For the astronaut to begin or terminate EV activity, it is necessary that he pass through an EVA hatch. The hatch size, the ingress/egress aids, the type of life support system used, and the possible need for cargo transfer must be considered prior to EVA hatch design or selection.

The dimensions of the Gemini hatch (24" to 31" wide x 34" high) provided adequate astronaut passage while using either the Life Support Umbilical (LSU) or a Portable Life Support System (PLSS) (see Figure 5-1). This hatch was used on all Gemini EVAs and is being employed as the Airlock Module EVA hatch on Skylab. The Skylab Program will include the first mission to utilize a module specifically designed for astronaut (plus cargo) transition to and from an EVA configuration without having to depressurize/repressurize the primary vehicle. This module has a cylindrical midsection to provide structural integrity and to enhance crewman mobility (see Chapter III, Section 3.3).

The EVA hatch on the Apollo Command Module is 21.5" to 25.5" wide x 26.5" high (see Figure 5-2). The Lunar Module EVA hatch which accommodated the A-7L-B pressure suit and the PLSS is 32" to 34" wide x 32" high. The minimum

FIGURE 5-1: Gemini EVA Hatch

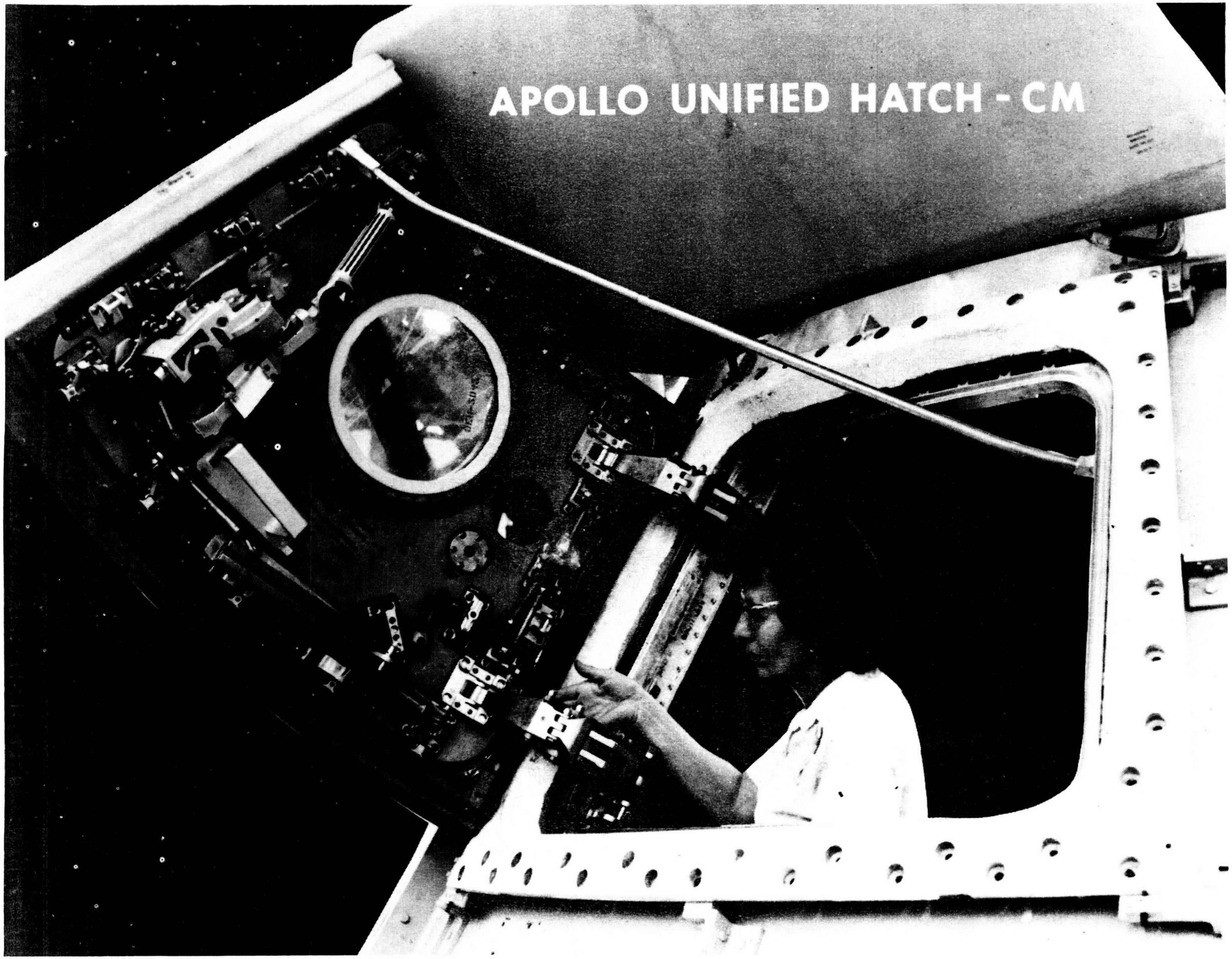


FIGURE 5-2: Apollo Command Module Unified Hatch

hatch size for crewman ingress/egress with the Apollo mobility unit is 30 inches in diameter (ref. 5.1).

During cargo transfer operations, fine control over the position of the body must be exercised. This is acheived through the use of personal restraints whose selection is based upon the nature of the forces to be applied. Less fine control is necessary during the actual ingress/egress of the astronaut unless the confinement through which he must pass is overly restrictive or unless contacting the edge of the opening will cause damage to the space suit or equipment.

To aid in the ingress/egress, handholds and handrails have been provided which improve stabilization and controlled mobility when passing through the EVA hatch. In the Gemini missions, nominal hatch ingress/egress activities required about five minutes. A variety of handrail and handhold shapes were evaluated on the Gemini missions. Of those evaluated, the astronauts preferred the rectangular cross section (.55" x 1.25"), which they felt increased their resistance to rotation and provided better control over body position (ref. 5.2). The standard Apollo and Skylab handhold or handrail is .62 inches thick by 1.25 inches wide and is mounted a minimum of 2.25 inches above the surface. Additional data are given in Section 3.4.2.

On Skylab, ingress/egress will normally be performed at the Airlock Module EVA (AM/EVA) hatch but can be performed at the Command Module hatch in contingency conditions. The crewmen will normally egress the AM/EVA hatch head first, face down, and ingress feet first, face down. The standard Apollo cross section handrails and handholds will be used for aids during ingress/egress. The primary aid to be used for these activities is a handrail located immediately below the AM/EVA hatch opening, where it can be located readily at the onset of egress activity (see Section 3.5).

Because of the duration and nature of the EV activity, two EV crewmen will be required. During cargo transfer through the hatch, one crewman will be located in the Airlock Module and the other located in the FAS workstation. Therefore, no ingress/egress with cargo is planned. The expected task completion times are four minutes for cargo transfer and two minutes for astronaut transfer, after the hatch is opened (ref. 5.3).

5.1.1.2 Workstation Ingress/Egress

To facilitate ingress/egress of the EVA worksites, handrails and handholds are provided for positioning the body while maneuvering into and out of the restraints. On the Gemini Program, the preferred handhold had a circular cross section within 1.38 inch diameter. Such handholds and handrails were used to provide body control while attaching waist tethers and foot restraints. The molded foot restraints (Dutch Shoes) used on Gemini XII proved to be the most effective of all foot restraints evaluated inflight up to that time. Maneuvering into and out of these restraints required that the crewman use the handholds/handrails while visually directing his feet into the heels of the restraints. He then rotated his feet to secure his toes in the restraints.

On Apollo 9, molded foot restraints were mounted at the LM hatch workstation for use during photography and thermal sample retrieval. Standard Apollo cross section handrails and handholds adjacent to the hatch (see Figure 5-3) were used successfully in maneuvering into and out of the restraints.

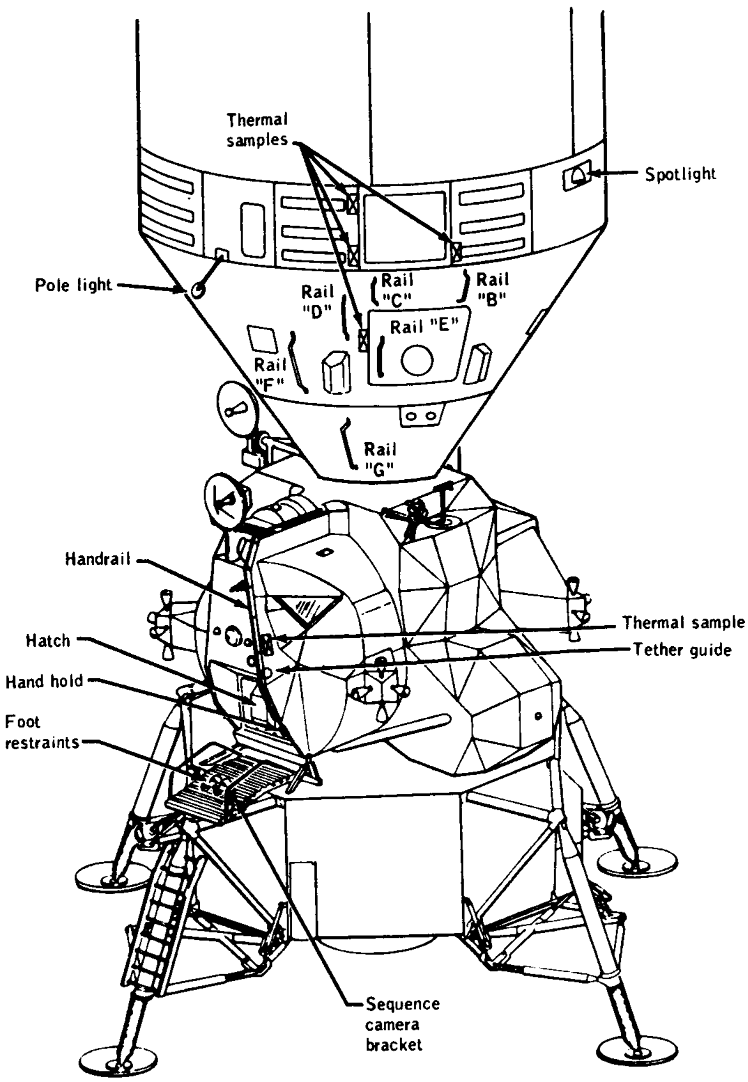


FIGURE 5-3: Apollo 9 Relative Spacecraft Positions and Location of Handrails and Thermal Samples

The command module pilots during the later Apollo transearth EVAs used adjustable foot restraints to retrieve camera cassettes from the Scientific Instrumentation Module (SIM) bay. Figure 5-4 depicts the handholds and handrails used to ingress/egress the command module hatch, translate to the SIM bay, and ingress/egress the foot restraints.

The following is a list and brief description of the ingress/egress aids at the Skylab workstations where EV activity will be performed. All handrails/handholds are of the standard Apollo cross section configuration (Figure 5-5).

- FAS Workstation (VF): As previously mentioned, the primary aid for ingress/egress will be the handrail at the AM/EVA hatch opening. The dual handrails and auxiliary handholds will also be used where necessary (see Section 3.5). Through simulation activity, the task completion time is expected to be approximately one minute (ref. 5.3).

- Center Workstation (VC): The intermediate handrail ("T-Bar") located near the VC workstation will be used to leave or approach the dual translation handrails and to leave or approach the primary aids for VC ingress/egress. These aids include two handrails located on the left and right vertical support members. Also, the rail located on the astronaut's protective screen can be used as an additional ingress/egress aid (see Section 3.5). Task completion time is approximately two minutes (ref. 5.3).

- Transfer Workstation (VT): In order for the astronaut to maneuver into or out of this workstation, it is necessary that he execute a 90 degree turn to permit proper foot placement. The solar shield handrail will be used for the ingress/egress aid (see Section 3.5). Task completion time is one to two minutes (ref. 5.3).

- Sun End Workstation (VS): The solar shield handrail and the "horseshoe" handrail will be used for ingress/egress activities. The "horseshoe" handrail is located on the solar end of the ATM canister between the S-082A and S-082B experiment aperture doors (see Section 3.5). Task completion time is expected to be one to two minutes (ref. 5.3).

Under nominal operating conditions, the astronaut will not transfer cargo while ingressing or egressing worksites.

5.1.2 Translation

5.1.2.1 Man Unaided

A number of unaided translations were performed on the Gemini program using a variety of handrails and handholds. Rectangular handrails were used on all Gemini EVAs to translate from the cockpit to the aft end of the spacecraft. The handrails were 0.55" x 1.25" cross section and were 1.5" off the surface.

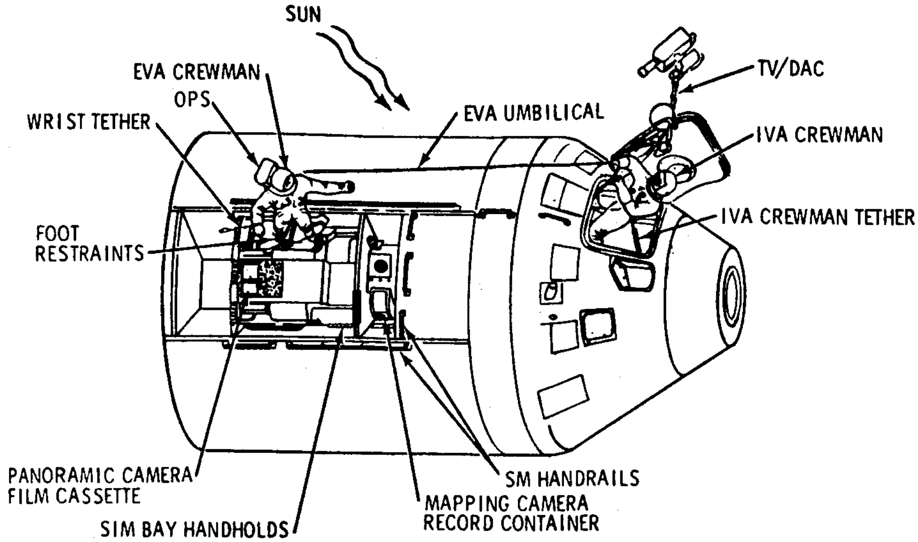


FIGURE 5-4: Apollo 15 Handrail/Handhold Location

The pilots translated along the handrails "hand beside hand" in a sideways direction because of ELSS chestpack configuration and limited suit mobility. The pilots reported that the rectangular cross section handrails were satisfactory for translation over distances up to eight feet and were useful as handholds when performing ingress/egress of hatches and worksites. Rectangular handrails were reported to be superior to circular cross section (cylindrical) handrails (as mentioned above) because they enabled the pilot to better resist rotation and better control his body position. The location of the rectangular handrails used on the Gemini program is shown in Figure 5-6.

On the early Gemini flights, attempts were made to use the umbilical as a translation and stabilization device, but the umbilical proved to be effective only as a distance limiter. One variation of this use was employed on Gemini X, when the pilot used the 50 foot umbilical to pull himself back to the cockpit hatch from the Agena target vehicle.

A telescoping, circular cross section handrail was installed on Gemini XII to facilitate translation from the spacecraft hatch to the spacecraft nose (see Figure 5-7). The handrail was deployed manually to a length of 99 inches after the cabin hatch was opened. The handrail was constructed in four sections ranging from 1-3/8" to 0.625" in diameter. The pilot reported that the flexibility of the handrail was undesirable for stabilization during translation to the spacecraft nose and for use as a handhold for changing body position.

On Apollo 9, to evaluate transfer systems, the Lunar Module pilot translated along the LM handrail to the point where it turned and crossed the top surface of the LM. All translation efforts were performed with minimum effort, and the crewman rated the rail excellent for translation capability and for body position control. Data show a low metabolic expenditure and heart rate during EV activities utilizing this rail.

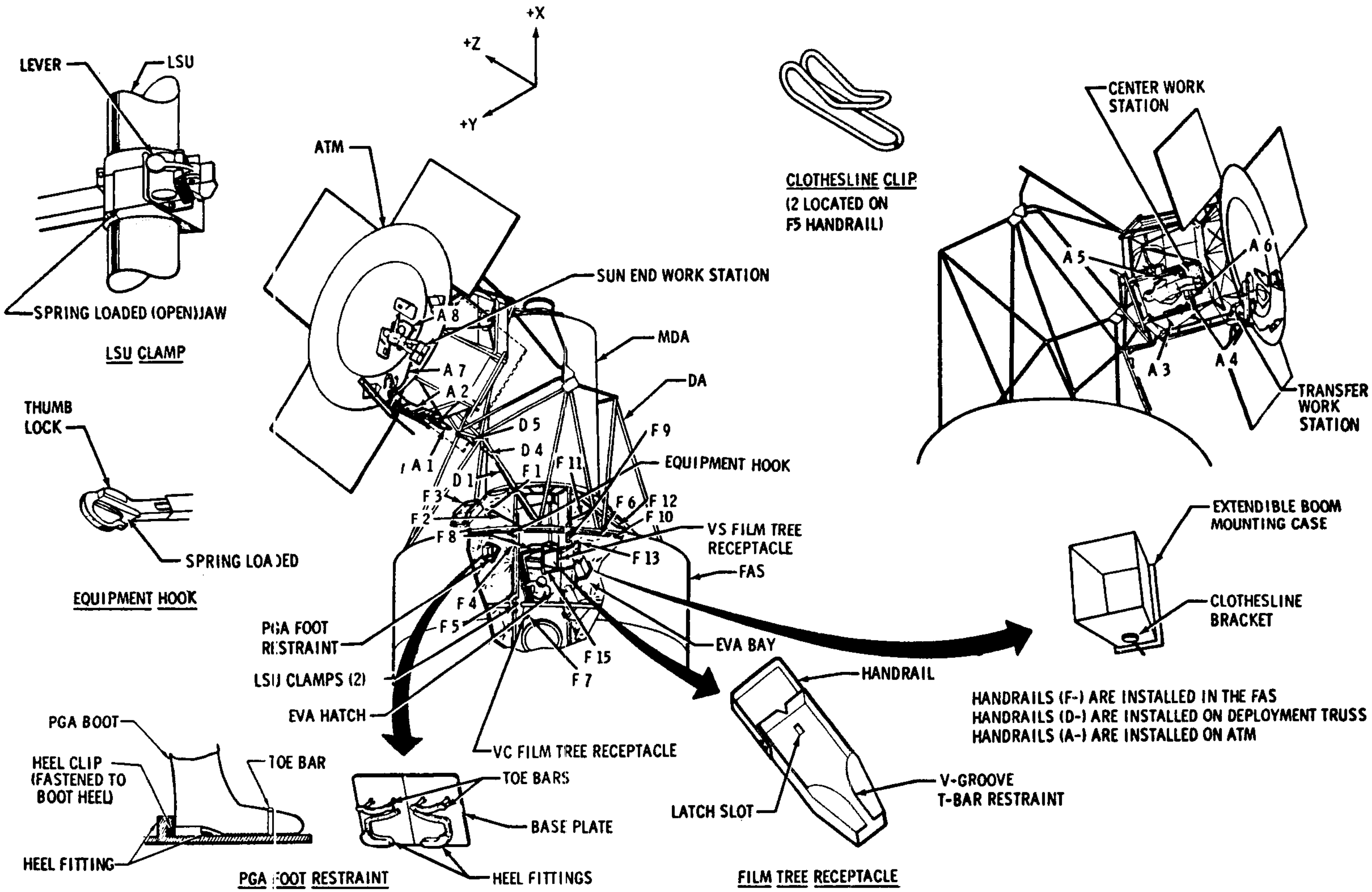


FIGURE 5-5: Skylab External Restraints and Mobility Aids

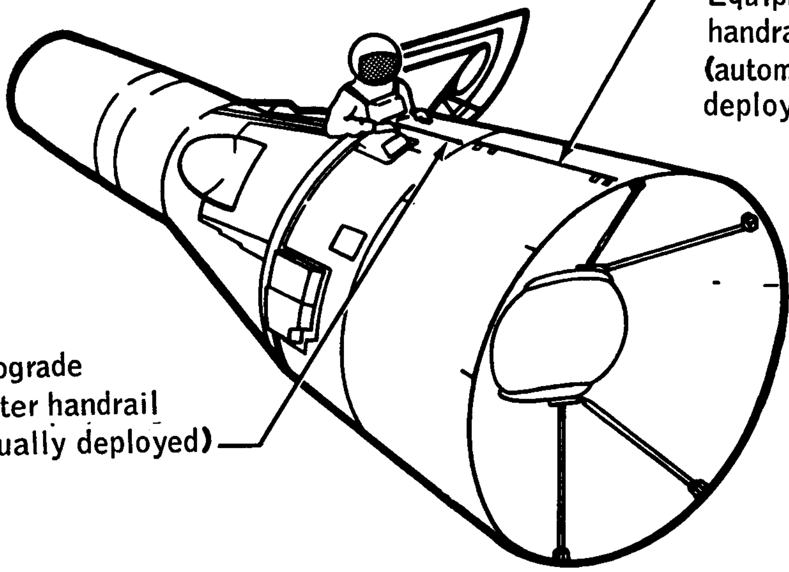


FIGURE 5-6: Rectangular, Extendible Handrails on Gemini Spacecraft Adapter

During the transearth extravehicular activity portion of the Apollo 15 mission, the crewman egressed the CM hatch and translated to the Scientific Instrumentation Module bay to retrieve the panoramic and mapping camera cassettes. The rectangular handholds and handrails were placed near the hatch and on either side of the SIM bay.

The crewman made a total of three trips to the SIM bay area, twice to fulfill prescribed EVA procedures and once to investigate faulty equipment. The complete EV operation (including ingress/egress activities) required about sixteen minutes and was performed in an efficient manner.

5.1.2.2 Man Aided

The Hand Held Maneuvering Unit (HHMU) is the only maneuvering device evaluated during Gemini EVA. This device was used on Gemini IV, X, and XI. On Gemini X, the pilot used the HHMU to translate approximately 15 feet back to the spacecraft after drifting away. He also successfully translated via the HHMU from the spacecraft to the nearby target vehicle. The Gemini X EVA, the most complete orbital evaluation of the maneuvering unit, indicated that the device could be used effectively to perform translation maneuvers with a zero to two pound thrust level (ref. 5.2).

The Astronaut Maneuvering Unit (AMU), a more complex unit than the HHMU, was planned for evaluation on Gemini IX-A. However, excessive workloads exerted by the pilot in preparing for AMU evaluation eventually led to the termination of the EVA without such evaluation.

No aided translation was conducted on the Apollo program, and none is planned for Skylab outside the vehicle.

FIGURE 5-7: Telescoping Handrail Used on Gemini XII

5.1.2.3 Man/Cargo Unaided

In all the Gemini EVAs, some cargo items such as experiment samples and equipment were transferred through the cabin hatch. Some items were also transferred from the adapter section of the spacecraft to the cabin and from the target vehicle to the cabin.

Cameras were deployed and installed on all Gemini EVAs which required transfer of these items through the cabin hatch to their mounting points. In addition to these, micrometeorite packages were retrieved on Gemini IX-A, X, XI, and XII. Several of these micrometeorite packages were retrieved from the adapter section of the spacecraft while others came from the Agena target vehicle.

The major conclusions drawn from package handling operations on the Gemini Program were that no significant problems are introduced by handling small packages, if they are securely tethered.

The Apollo Program represented the first major cargo transfer operations attempted in space. On Apollo 9, small thermal samples were retrieved and returned to the CSM and LM. On later missions the EVA crewman translated to the SIM bay to retrieve experiment equipment. The largest package handled in the EVA was the 24" diameter panoramic camera cassette weighing 85 pounds. This cassette was successfully transferred to the CSM hatch through use of handrails and handholds plus a wrist tether (ref. 5.4).

The Skylab Program will include no aided translation (i.e., AMU, HHMU, etc.) during the EV mode. Certain mobility units (experiments M-509 and T-020) will, however, be evaluated during IVA. The primary mode of EVA translation will utilize the dual handrails which provide a route between the VF, VC, and VT work areas; these rails are the standard Apollo cross section. By using the rails, the astronaut can translate at an average velocity of 0.5 to 1.0 ft/sec, and the expected translation completion times are:

VF to VC	-	3-4 min.
VC to VT	-	2-3 min.
VT to VS	-	2 min.
VS to VT	-	1-2 min.
VT to VC	-	2-3 min.
VC to VF	-	3-4 min.

Under normal translation procedures, the astronaut will not be transporting cargo.

5.1.2.4 Man/Cargo Aided

No cargo handling operations have been performed on orbit with maneuvering aids. The Gemini X mission included plans for HHMU use in transferring equipment samples from the target vehicle. However, the pilot used the umbilical to make the return with samples to the cabin.

No aided cargo handling EVAs have been performed on the Apollo Program, and none are planned for Skylab. Tests inside the Skylab Workshop will be conducted using the M-509 Astronaut Maneuvering Research Vehicle (AMRV) and the T-020 Foot Controlled Maneuvering Unit (FCMU). It is expected that these experiments

will provide very useful data on maneuvering and stabilization with cargo and aids.

5.1.3 Worksite Activities

The Gemini and Apollo Programs and their supporting simulations have provided considerable insight into the activities an EVA crewman can perform at a worksite. The early Gemini EVAs indicated that body position control, while performing tasks, was critical to maintaining acceptable workload levels and to exerting certain torques. A number of restraints concepts were developed and tested on the Gemini Program which largely determined what activities could be performed. This section discusses the body position control characteristics afforded by various restraints and the tasks that have been performed with these restraints.

5.1.3.1 Body Position Control

A wide variety of worksite restraint devices were tested during the Gemini EVAs. These devices included tethers, handholds, and foot restraints which afforded the astronaut body position control while he was performing tasks at a worksite. A detailed description of the evolution for restraints from waist tethers to molded foot restraints is given in Chapter II and will not be repeated here. However, the findings of the Gemini EVAs defined the restraint devices that were used on Apollo missions and will be used on Skylab.

In the early missions, the preferred restraints for most EVA tasks were the molded foot restraints. These devices were used on several Gemini and Apollo flights and were rated as "far superior" to all other restraints evaluated. In addition to the molded foot restraints, handholds and handrails were provided to afford stabilization and torque resistance. With these restraints, crewmen were effectively able to accomplish the tasks required for these missions.

Since the molded foot restraints allowed the crewman to pivot from side to side and also backward and forward about his ankles, reach envelopes with these devices were larger than with most other restraints (e.g., waist tethers, handholds). For example, on Gemini XII, the crewman was able to lean backward 90 degrees, roll about ±45 degrees, and yaw sideward almost ±90 degrees (ref. 5.5).

At all Skylab workstations, the astronaut will utilize handholds and handrails to position or stabilize himself for the ingress/egress of the foot restraints. The foot restraints consist of toe bars and heel clips and permit the astronaut to maintain complete body position control. The foot is inserted under the toe bar, and the heel is then rotated into place.

5.1.3.2 Tasks

The Gemini EVAs have shown that man is capable of effectively performing several operations or tasks while outside the space vehicle. During EVA on the early Gemini flights, cameras were mounted, handrails deployed, tethers attached, a nitrogen line connected and disconnected, experiment samples

collected, and photographs taken. On Gemini XII a task panel was mounted in the adapter section of the spacecraft to evaluate tasks that may be required for future missions. Using molded foot restraints and handholds, the crewman was able to apply forces in excess of 25 pounds and to perform connector alignment and cutting tasks. The crewman also applied a torque exceeding 200 in.-lbs. with a 9 inch torque wrench. Using the 5 inch Apollo torque wrench, a torque greater than 100 in.-lbs. was applied. While in the molded foot restraints, the crewman was able to disconnect and connect electrical leads and to cut wire strands and a fluid hose (refs. 5.2 and 5.5).

EVA on the Apollo 9 mission included photographic and sample collection tasks and an abbreviated evaluation of translation and body attitude control capability using the EVA transfer handrails.

EVA on Apollo 15 and 16 involved the retrieval of camera cassettes (the heaviest of which weighed 85 earth pounds) from the panoramic and mapping cameras in the Scientific Instrument Module (SIM) bay during the first EVA excursion of these missions. The second excursion involved retrieval of a 23 pound mapping camera cassette, and, on Apollo 15, a third trip was made to inspect equipment in the SIM bay. EVA on the Apollo 17 flight is expected to follow this same general program of activities (ref. 5.4).

Typical force applications that will be required at the Skylab workstations include pushing, pulling, lifting, squeezing, and rotating. For example, certain film magazine access doors involve pushing a handle to unlock and pulling to open it. Removal of certain film magazines involves squeezing a handle to release, lifting, and pulling to remove. All of the forces required to perform the EV operations will be within a 10 to 25 lb. range. Through extensive simulation activity, it has been found that, given the proper access and restraint systems (such as those discussed) and other associated systems, the astronaut can satisfactorily perform activities within the constraints imposed by time and physiological limits.

5.2 BIOMEDICAL AND PHYSIOLOGICAL CHARACTERISTICS

5.2.1 Introduction

The primary medical objectives of the early manned spaceflights were to: (1) assure crew safety, (2) assure mission completion and execution of those activities contributing to mission success, and (3) to further the understanding of the biomedical changes incident to manned spaceflight. The Mercury project proved that man could survive brief exposures to spaceflight. The Gemini flights, with five orbital EVA missions, investigated man's physiological systems in more detail and demonstrated physical changes peculiar to the space environment involving red blood cell mass, cardiovascular conditioning, bone density, exercise capability, muscle nitrogen, and body weight.

The Apollo Program, with its orbital and extended lunar EVA missions, allowed the continuation of the medical studies initiated during the Gemini flights. The Apollo flights provided opportunities to evaluate the space environment without the stringent degree of confinement associated with the Mercury and Gemini Programs. In the Apollo spacecraft, for example, the

crewmen were able to move about the cabin, to stand upright, and to exercise (ref. 5.6).

During the Apollo flights, physiologic changes were observed in relation to the duration of spaceflight exposure of each crewman on each flight. The knowledge derived from these observations concerning the physiological causes of these changes in man during spaceflight has become part of subsequent studies which have endorsed longer flights.

With the Apollo lunar missions came an additional medical objective -- to prevent the back contamination of our biosphere. Approximately three years prior to the Apollo 11 mission (first lunar EVA), programs were initiated to provide quarantine operations to preclude the possibility of contaminating the earth's biosphere with lunar organisms. The quarantine procedure began with the closure of the Lunar Module hatch on the lunar surface and continued for approximately 21 days postflight. As part of this procedure, a series of complicated and detailed tests were conducted in the NASA Lunar Receiving Laboratory. No evidence of any infectious disease or any organism could be cultured, nor were there any adverse effects on animals or plants exposed to the lunar material. The only positive biological findings were the bactericidal properties of the lunar material upon known cultures and the marked enhancement of growth in plant seedlings and tissue cultures (ref. 5.7).

The ultimate medical objectives in the United States' manned spaceflight programs are to provide the necessary medical operational support to enable man to fly safely and to provide answers to the following questions (ref. 5.7):

- How long can man be exposed to the spaceflight environment without producing a significant physiologic performance decrement?
- What are the causes of the changes which are observed?
- Are preventive measures or treatment needed and, if so, what is best?

A summary of the stresses that the crewman is exposed to during spaceflight is shown in Figure 5-8. Many of these stresses can be simulated in ground based studies. However, it is not possible to duplicate actual flight situations, since extended weightlessness and the real emotional stresses of spaceflight cannot be duplicated in ground studies. The scientific questions relative to manned spaceflight are as diverse and inexhaustible as are those common to earthbound laboratories. There is no foreseeable end point for space-related biomedical and physiological studies (ref. 5.7).

Although the purpose of this section of the <u>EVA Guidelines</u> document is to discuss the biomedical and physiological characteristics specifically associated with the crewman in the orbital extravehicular environment, most of the physiological EVA parameters are within the total manned spaceflight medical program. Therefore, while subsequent discussions will be primarily directed toward man and his subjection to orbital EVA, they will also touch on certain associated medical problems. Since the biomedical aspects of EVA are part of the total spaceflight medical descipline, a summary of these medical studies

is contained in Appendix D. Included in the summary is a synopsis of the medical programs scheduled for the Skylab missions.

Full pressure suit
Confinement and restraint
100% oxygen = 5 psia atmosphere
Changing cabin pressure (launch and reentry)
Varying cabin and suit temperature
Acceleration -- G force
Weightlessness
Vibration
Dehydration
Flight plan performance
Sleep need
Alertness need
Changing illumination
Diminished food intake (varying with crewman)

FIGURE 5-8: Spaceflight Stresses

5.2.2 Orbital EVA Medical Objectives

The insurance of the safety and well-being of the extravehicular crewman (rather than the collection of specific medical data) has been the primary consideration of the in-space medical monitoring program during past orbital EVA missions. The biomedical/physiologic data collected during the orbital EVAs formed an integral part of the total medical monitoring program, but these data were basically associated with the crewman's energy expenditure during various extravehicular functions. The metabolic cost of EVA tasks associated with the earlier Gemini missions was of major concern in planning for lunar EVA and intravehicular activity in the larger Apollo spacecraft. Although there were no actual metabolic measurements inflight during the Gemini EVA missions, metabolic cost calibration was determined preflight by use of bicycle ergometry and was correlated to heart rate measurements which were taken inflight. The problems encountered because of the high metabolic rates associated with the earlier orbital EVA functions were primarily attributed to the lack of proper crewman restraints and lack of adequate life support systems (specifically, the inadequate means for metabolic heat removal). With the correction of these systems and the introduction of space suits with improved mobility, the

EVA metabolic cost problem was corrected. With respect to metabolic rate predictions for lunar EVA and for Apollo intravehicular activity, no problems of significance were encountered. Further, since the Skylab Program is equipped with orbital EVA hardware developed to preclude the problems associated with the earlier orbital EVA missions, no metabolic load difficulties are anticipated. The primary medical objectives for orbital EVA in the 1980 time frame are still monitoring for crew safety and well-being, but these objectives will be extended to include work rate control through real-time metabolic load predictions. The monitoring of heart rate, oxygen consumption and liquid cooled garment heat balance are the current methods used for obtaining inflight metabolic data. These methods are discussed in Section 5.3.

5.2.3 Spaceflight Physiological Parameters

There are several important physiological parameters associated with orbital EVA that are of major interest in the design and selection of systems and equipment to be used on future EVA missions. The parameters discussed in the following subsections deal with: (1) the atmospheric environment to which the crewman is subjected (both in the spacecraft and in his space suit), (2) the prebreathing requirements associated with changes in pressure and breathing medium, (3) the radiation and micrometeoroid environment and, (4) the crewman's adaptation to weightlessness. Although emphasis in this section is directed toward the space-suited man in the orbital extravehicular environment, mention of the environmental characteristics in the spacecraft itself are essential in the discussion. Therefore, the spacecraft parameters affecting the man in his EVA operations will be presented in areas where they will enhance insight into the EVA physiological parameters.

5.2.3.1 Atmospheric Environment

There are five important factors concerning the atmospheric environment of the spacecraft and of the space suit, while it is exposed to the extravehicular environment. In order for man to perform safely in the space environment, adequate attention must be given to: (1) total ambient pressure, (2) oxygen partial pressure, (3) carbon dioxide partial pressure, (4) thermal parameters, and (5) possible atmospheric contamination. A brief discussion of these points is appropriate.

(1) Total Ambient Pressure

When the total ambient pressure approaches 47 mm Hg, the effective vapor pressure of fluids at body temperature gives rise to excessive evaporation. This results in the formation of vapor bubbles in tissues, blood vessels, and body cavities. The location of vapor formation in the body is determined by such local factors as temperature, hydrostatic pressure, tissue elasticity, solution concentration, and presence of gas nuclei. The large venous channels at the center of the body temperature core are sites of early bubble formation, causing "vapor lock" of the heart. Vapor pockets subsequently form in the loose subcutaneous tissue, in the aqueous humor of the eye, and in the brain. When all or part of the human body

is exposed to near-vacuum conditions, fluids in the body vaporize suddenly, the result being marked swelling and mechanical disruption of body tissues (ref. 5.8).

To provide a viable spaceflight atmosphere, the United States has used a spacecraft environment of 100% oxygen at 5 psia through the Apollo 6 flights. A mixture of approximately 60% nitrogen has been used in the remaining Apollo flights (Command Module only) during checkout and launch, with a specified enrichment to essentially 100% oxygen prior to mission completion. The change from a pure oxygen environment to a cabin gas mixture at launch was adapted as a safety precaution following the Apollo Command Module fire in 1967. The partial pressure of oxygen in the Command Module cabin is not allowed to drop below that at sea level on earth (pp O_2 of 3.1 psia). Methods of removing the oxygen diluent include cabin leakage and cabin purge through overboard dump nozzles and replacement with 100% oxygen. An oxygen analysis conducted on the Apollo 7 mission recorded the oxygen enrichment profile shown in Figure 5-9.

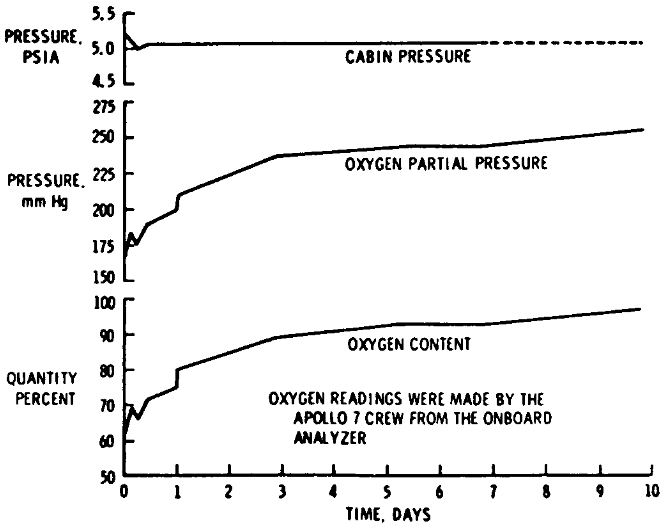


FIGURE 5-9: Apollo 7 Cabin Oxygen Enrichment Profile (10-Day Flight)

The Apollo crewmen remove their space suit helmets and gloves usually within the first half hour, and always within the first hour after launch. The space suit is doffed completely when convenient, and flight coveralls are donned for most of the mission. Since the Apollo 7 mission, space suits have not been worn for reentry, but donned only for EVA and critical mission phases such as separation and docking activities (ref. 5.7).

The space suits used by the United States during the Gemini and Apollo orbital extravehicular activities have been maintained at a pressure between 3.5 and 3.9 psia. The spacecraft umbilical systems, used on all but the Apollo 9 orbital EVA mission, supplied 100% oxygen to the space suit. The Apollo 9 EVA used a self-contained portable life support system which also provided suit pressure at approximately 3.7 psia and 100% oxygen. Each environmental control system (ECS) used to support the space suit during orbital EVA was designed to limit the carbon dioxide partial pressure to approximately 7.6 mm Hg for nominal operations and 15 mm Hg for contingency situations. The carbon dioxide level is maintained either through exhausting a percentage of the expired gas mixture to space or chemical absorption by lithium hydroxide in a closed recirculating system.

In the USSR's three-man spacecraft, a "normal" atmosphere of approximately 20% oxygen and 80% nitrogen at a pressure of about 14.7 psia is used. The use of a 14.7 psia atmosphere eliminates the problem of prebreathing prior to launch and allows a totally "shirtsleeve" environment during an orbital mission. However, if an EVA mission is a part of the total program and the space suit operates at a pressure lower than 14.7 psia, prebreathing must be performed prior to exit from the space cabin. Another factor to consider in the 14.7 psia spacecraft environment is the possibility of a sudden loss of cabin pressure. Dysbarism ("bends") are more likely to occur with a rapid decompression from a "normal" atmosphere than from a 100% oxygen, 5 psia environment. Gases which are normally carried in solution by the bloodstream will become gas bubbles when the surrounding pressure is suddenly lowered. Since the occurrence of gas bubbles is a function of the type of gas in solution, nitrogen (which dissolves with relative ease in the bloodstream) easily comes out of solution. Oxygen, which forms chemical bonds with the blood substances, does not present as critical a vapor bubble problem but does diffuse into the evolved bubbles of gas. By employing 100% oxygen at a pressure lower than normal earth pressure, crewmen in a spacecraft are not subjected to as great a risk of dysbarism as are those employing the nitrogen-oxygen mixed gas atmosphere and higher pressure.

In the United States' Apollo Command Module, the environmental control system is designed to maintain a cabin pressure above 3.5 psia for 5 minutes after a 1/2 inch-diameter puncture. Should loss of cabin pressurization occur, life support in the space suit mode will be provided for a sufficient duration to permit repair operations or safe return of the crewmembers (ref. 5.10).

Certain advantages and disadvantages are evident concerning the use of a "normal" atmospheric environment or a reduced pressure, pure oxygen environment. Some of the considerations may include weight factors, safety, fire hazard, material outgassing, and prolonged breathing of pure oxygen. The full treatment of the selection trade-off necessary in choosing a spacecraft cabin atmosphere is beyond the scope of this document.

(2) Oxygen Partial Pressure

Man's physical functions are unimpaired at an oxygen partial pressure of 3.1 psia in a 14.7 psia environment. At oxygen partial pressures of less than 2.5 psia, a deficiency of oxygen reaching the body tissues (hypoxia) is introduced. Tissues most sensitive to oxygen deficiency, such as the central nervous system (brain and eyes), cannot function without oxygen. Muscles can function temporarily without oxygen, but, in the process, they build up toxic fatigue products that limit their further activity. The heart, which consists entirely of red muscle tissue, is almost as sensitive to oxygen deficiency as the central nervous system. Prolonged exposure to oxygen pressures only slightly below 2.5 psia causes impairment of vision, mental processes, and coordination. Acute hypoxia results in progressive impairment and can cause death (ref. 5-11).

The visual functions appear to be the most sensitive to hypoxia. Figure 5-10 summarizes some of the thresholds of visual determination as a function of oxygen partial pressure.

Hypoxia can impose a significant problem in the spacecraft and expecially in the extravehicular space suit environment. Although the present space suits are operated at a nominal pressure of 3.7±.2 psia with 100% oxygen, the presence of carbon dioxide, water vapor and other contaminants, combined with a high EVA work rate, can cause an oxygen deficient condition when operations are being conducted in the lower pressure range. For any one individual, the symptoms of hypoxia may be unpredictable in its onset and course, and individual susceptibility varies widely except in instances of severe oxygen deficiency. These conditions make it difficult to identify or predict hypoxia problems in the space-suited crewman because of the many variables in man.

Of particular interest in the planning of orbital extravehicular activities is the rate of oxygen consumption and of carbon dioxide and heat production to determine the quantity of oxygen (or mixed gases) that must be supplied to the crewman operating in a space suit. The quantity of oxygen used by the EVA crewman depends on the workload (see Table 5-1) but has not been a factor in the later Gemini and the Apollo EVA missions since a much greater quantity of oxygen is required to accomplish carbon dioxide washout and to avoid hypoxia than can be consumed by the crewman.

At oxygen partial pressures greater than 7.4 psia (≈380 mm Hg), hyperoxia symptoms begin to appear as a function of time (Figure 5-11). The first symptoms usually appear in the respiratory tract and include such conditions as bronchitis and pulmonary edema, causing substernal distress, coughing, dizziness, fainting and convulsions. Although the atmospheres of United States' spacecraft and space suits are nominally operated at an elevated partial pressure of oxygen, the total pressure has usually been low enough to preclude major concern with hyperoxia

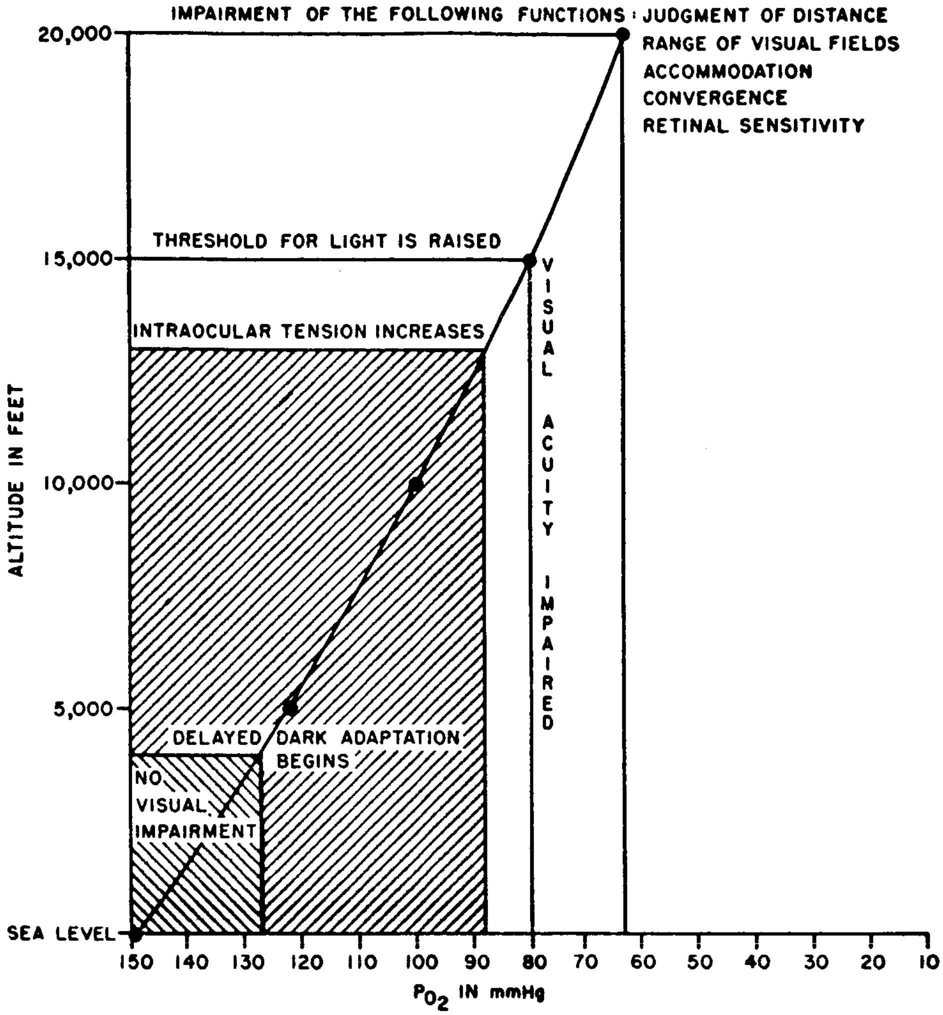


FIGURE 5-10: Visual Functions Impairment Produced by Hypoxia

during EVA on past and current space programs. The spaceflight medical programs are concerned, however, with the relationship between the low pressure 100% oxygen environment and the reduction of red cell mass during certain spaceflights. The etiology of the loss of red cell mass is as yet undetermined, but a strong evidence of an indirect nature from current studies may provide a correlation between this loss of mass and the use of the 100% oxygen atmosphere (ref. 5.13).

The advent of the higher pressure atmospheres of the Space Shuttle and Space Station, and the corresponding use of 8 to 14.7 psia space suits, will require additional study and consideration of oxygen toxicity. The physiological relation between the percentage of

TABLE 5-1: Physical Work Classification by Severity (ref. 5.12)

Work Classification	lb O_2/hr	kcal/min	Btu/hr
Very light work *	below 0.10	below 2.5	below 595
Light work *	0.10 - 0.19	2.5 - 5.0	595 - 1190
Moderate work *	0.19 - 0.28	5.0 - 7.5	1190 - 1785
Heavy work *	0.28 - 0.38	7.5 - 10.0	1785 - 2380
Very heavy work	0.38 - 0.47	10.0 - 12.5	2380 - 2975
Extremely heavy work	over 0.47	over 12.5	over 2975

*Space Suit Range

oxygen in the atmosphere of closed environments and the total pressure of that atmosphere is shown in Figure 5-12. The data contained in the figure is based on continuous exposure for one week or more. The clear unimpaired performance zone, bounded by the hatched lines, indicates the range of variations that can be tolerated without performance decrement.

(3) Carbon Dioxide Partial Pressure

The physiologically acceptable carbon dioxide concentration limits for breathing gas in the 3.7 psia space suits has been set at 7.6 mm Hg for nominal operations and 15.0 mm Hg during heavy workloads (short term) or contingency conditions. Concentrations of carbon dioxide in excess of these limits may cause a number of symptoms, including visual distortion, dizziness, mental disorientation, stupor, etc., until unconsciousness is reached. The toxic effects of carbon dioxide are summarized in Figure 5-13 and are expressed in terms of percent of carbon dioxide at sea level in one atmosphere. An expanded list of the symptoms associated with carbon dioxide toxicity is shown below:

- Dyspnea
- Headache
- Stomach ache
- Dizziness
- Sweating
- Salivation
- Increased motor activity
- Restlessness
- Loss of control over limbs (overactivity)
- Loss of balance (spatial disorientation)

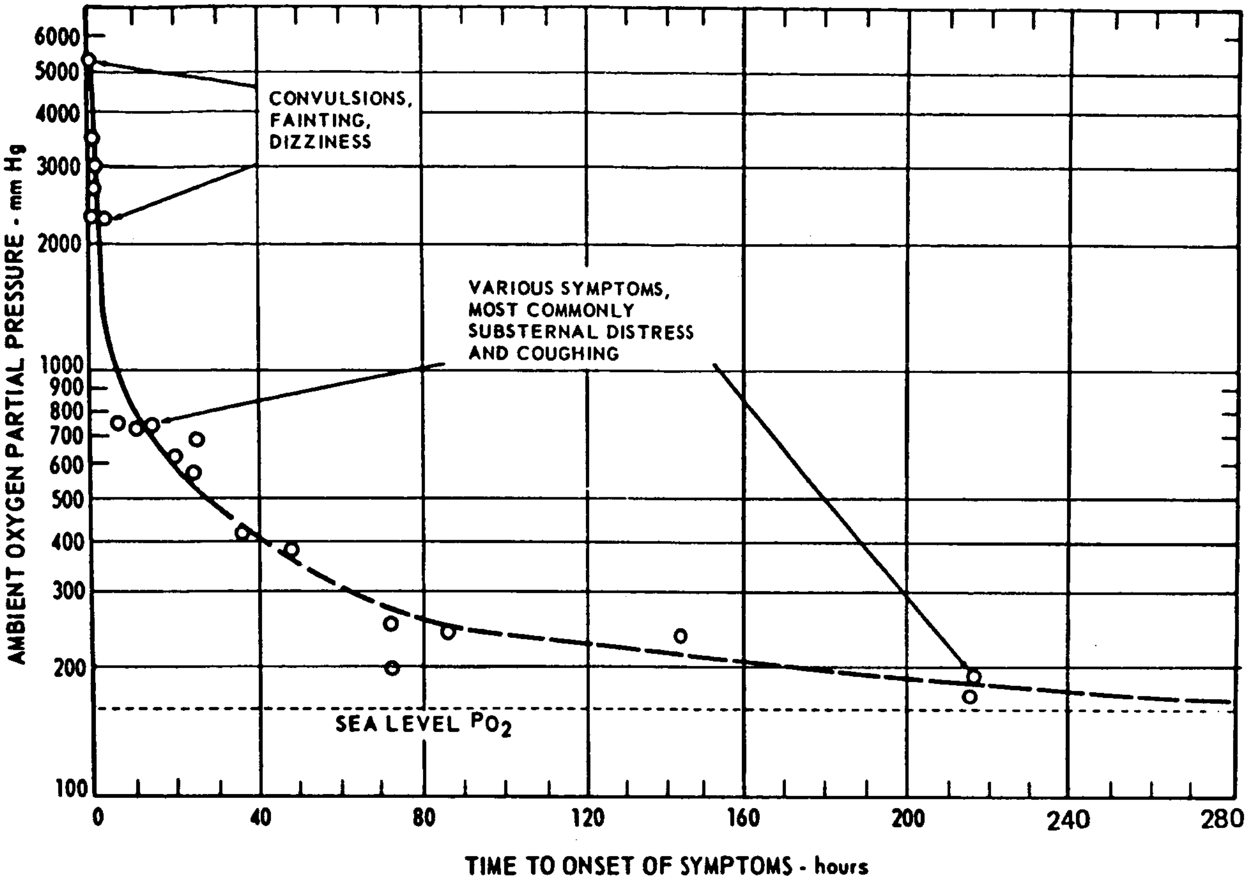


FIGURE 5-11: Times to First Symptoms of Oxygen Toxicity

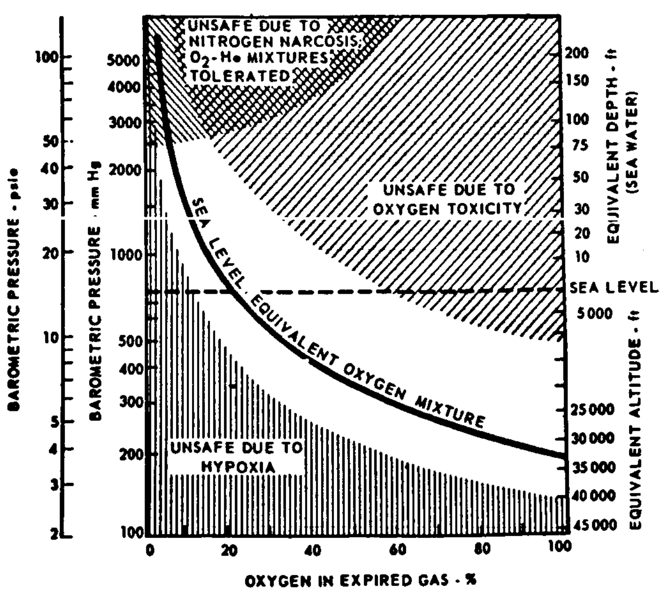


FIGURE 5-12: Effect of Barometric Pressure on Oxygen Required

Numbness of extremities

Cold sensations

Warmth sensations

Mental disorientation

Color distortion

Visual distortion

Irritability

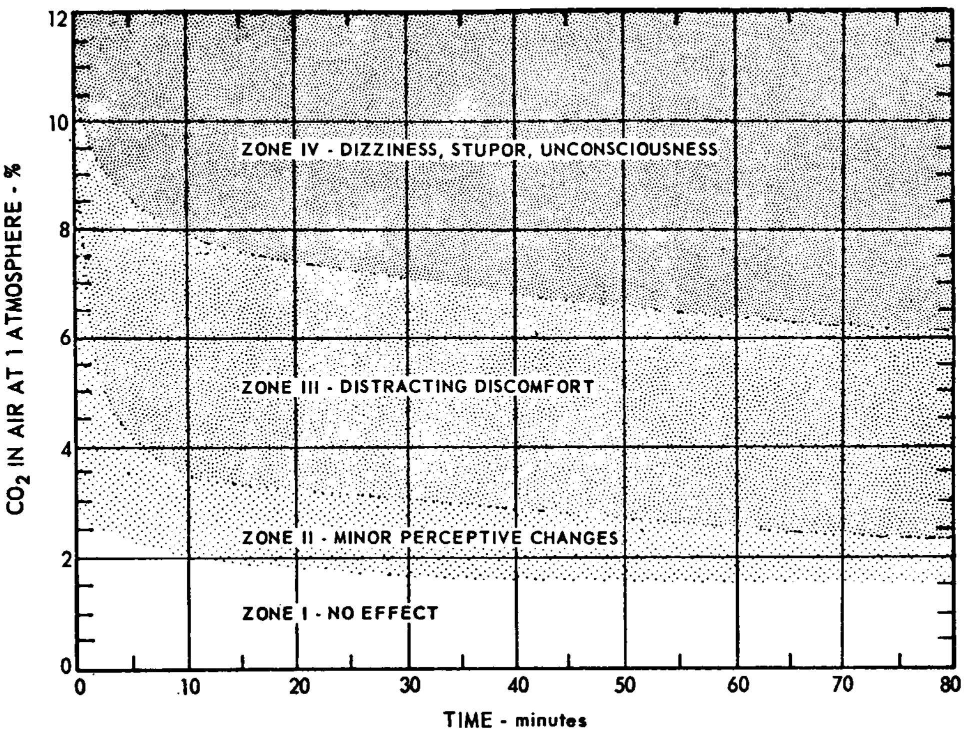


FIGURE 5-13: Toxic Effects of Carbon Dioxide at One Atmosphere

Maintaining carbon dioxide levels at physiologically acceptable limits in the space suit during EVA is of major concern. In all space suit systems, carbon dioxide control is dependent upon the ventilation gas moving the carbon dioxide away from the oronasal area so that it cannot be rebreathed. Carbon dioxide buildup is thus a function of ventilation flow rate, helmet geometry, ventilating duct design and the activity level of the crewman, assuming a normally functioning environmental control system.

The crewman's oronasal area where gas exchange does not occur includes the mouth, nostrils and bronchi. Exhausted gases remain in these areas (Figure 5-14) and are rebreathed during the following inhalation. The use of equipment such as a breathing mask or space suit helmet adds to this "dead space" and increases the proportion of expired air that is rebreathed unless removal precautions are

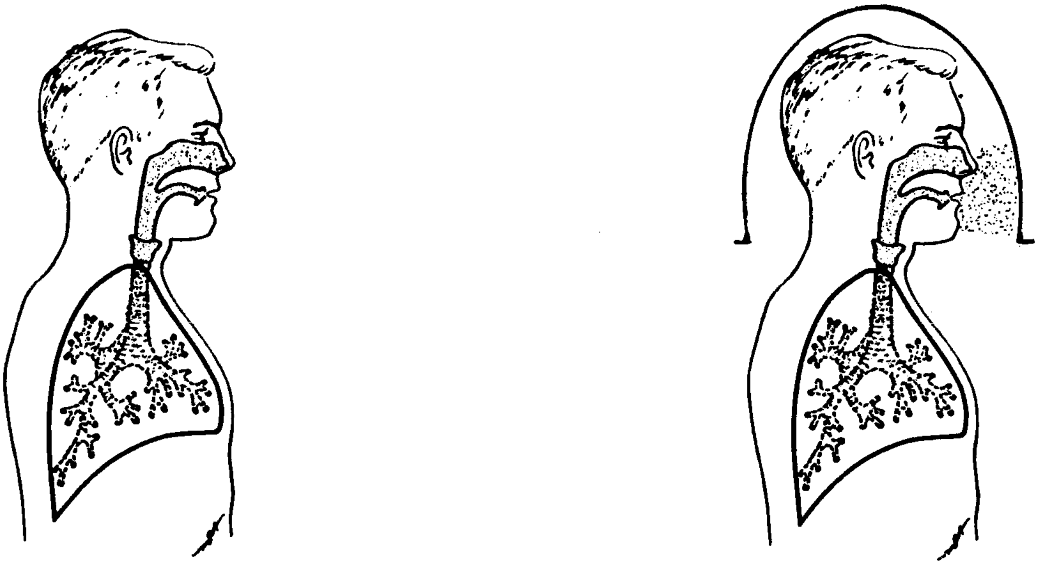


FIGURE 5-14: Anatomical and Equipment Dead Space

taken. In some of the Gemini EVA missions, the high level of physical activity may have resulted (though this proposition is unproven) in a concentration of carbon dioxide in the helmet sufficient to cause the increased respiration rate and the apparent exhaustion which resulted in the early termination of some EV activities. Although there was no measurement of carbon dioxide concentration in flight, there was an increase in CO_2 concentration during periods of heavy work in the ground testing of the EVA life support system. The Gemini environmental control system was designed to provide a nominal flow rate of 11.5 cubic feet per minute (cfm) of oxygen to the torso of the suit for thermal comfort and carbon dioxide washout. Approximately 6 cfm of the flow was ducted directly to the helmet area to assist in carbon dioxide washout and to provide oxygen for breathing (ref. 5.14).

The Apollo environmental control system supplies a flow rate of approximately 12 cfm of 100% oxygen to the space suit with a 50% distribution to the helmet area via a flow diverter valve located on the suit. Several tests were conducted prior to and following the Gemini missions to determine the carbon dioxide buildup in space suits during various workloads. Both the Gemini and Apollo space suits were tested. The data from tests conducted at the Manned Spacecraft Center in 1969 are shown in Table 5-2. The results of these tests indicated that, at the present design flow rates, carbon dioxide buildup in both space suits exceed the established physiologically acceptable limits of 7.6 mm Hg at work levels of approximately

TABLE 5.2: Mean Carbon Dioxide Levels During Spacesuit Activity

GEMINI SPACESUIT				
Metabolic Rate BTU/HR	Flow Rate-CFM			
	8	11.5	18	23
	mm Hg			
801-1200	5.3	4.3	1.7	0.9
1201-1600	7.0	5.7	2.7	1.4
1601-2000	10.1	9.9	5.9	3.8
2001-2800	19.1	12.8	6.2	4.3

APOLLO SPACESUIT							
Metabolic Rate BTU/HR	Flow Rate-CFM						
	3	4	5	6	7	8	9
	mm Hg						
1-400	6.3	3.9	2.7	2.0			
401-800	7.6	6.0	4.5	2.8			
801-1200	11.0	8.1	5.8	4.3			
1201-1600	15.5	11.7	8.1	5.7			
1601-2000	20.4	13.7	10.7	8.3		8.0	7.6
2001-2400	22.8	16.1	13.8	10.5	8.0	8.8	8.2
2401-2800		22.8	17.0	13.8		9.7	9.0

2000 Btu/hr. However, with the regulation of orbital EVA workloads and the results obtained from the Apollo 9 EVA missions (metabolic rate of 600 Btu/hr), no carbon dioxide problems are anticipated on future missions. The relocation of ventilation ducts in the space suit helmet may improve the carbon dioxide washout characteristics. Increased flow rates of the space suit environmental control system on future spacecraft could eliminate the potential carbon dioxide buildup completely.

(4) Thermal Parameters

In the "nominal" comfort state, man at rest will maintain a mean skin temperature of 91.4 ± 1.8°F and a rectal temperature of 98.6 ± 0.9°F. There will be no visible sweating, and the blood vessels near the surface of the skin will be slightly dilated. Any subsequent variation in metabolism or environmental conditions will initiate a change in the peripheral blood flow of the body (ref. 5.15). The body's regulatory system attempts to maintain a deep body temperature of approximately 98.6°F. The principal body thermoregulator mechanisms are changes in the rate of sweat production and changes in the blood flow to the skin area. The flow of blood to the peripheral blood vessels, controlled by vasoconstriction and vasodilation, is of major importance in monitoring crewman thermal balance in the spacecraft and space suit environments. Increasing the temperature of the environment or increasing the crewman's metabolic rate by activity will result in vasodilation to increase the heat exchange between the body core and skin. Sweating (or shivering) usually occurs before the limits of vascular regulation are reached and serves to reduce the load on the vascular system. Under high body temperature conditions, vasodilation and sweating occur simultaneously, thereby increasing the body's heat rejection capability. Vasoconstriction occurs when the deep body and/or skin temperature drops below the "comfort" temperatures mentioned earlier. Determination of the human body's thermal status in spaceflight requires analysis of a large number of variables. Many of these variables do not lend themselves to an exact mathematical solution but must be arrived at statistically from experimental data. These results must be treated with caution when applied to the small population represented by the current astronauts/flight scientists. Individual metabolic rates, health variations, tolerances, and motivation can cause wide deviations from predicted states and performances. Diurnal cycles are especially significant. As a rule, equipment provided to satisfy a primary functional requirement for biothermal protection and control is integral to the spacecraft/space suit environmental control systems and to the garment assemblies worn by the crew (ref. 5.15). A complete discussion of the many human body, clothing, and spacecraft environmental control mechanisms to maintain man in a state of thermal equilibrium is not in keeping with the intent of this document. (The reader may refer to the bibliography, Section 6, for sources of additional information.) The following information will describe only the major systems or methods used to provide biothermal protection and control in the spacecraft and space suit environments.

The Apollo environmental control system was designed to maintain a Command Module and Lunar Module cabin gas temperature of 75° ± 5°F, except during reentry when 100°F maximum has been permitted in the Command Module. The cabin relative humidity was limited to between 40 and 70 percent (ref. 5.10). Data from each of the flights (with the exception of the Apollo 13 translunar abort due to cryogenic oxygen loss) indicated that the Command Module temperature was maintained at about 70°F (range 62°F to 80°F), usually without the use of cabin fans. The Lunar Module cabin temperature was maintained between 65°F and 70°F, except during and immediately following depressurizations. Crew members felt cool during several occasions on the Apollo missions, particularly during translunar coast, but adjustment of the environmental control system promptly returned the temperature to the comfort level (ref. 5.7).

Maintaining the crewman within his thermal physiological tolerance limits is of major concern during orbital extravehicular activities. Accumulated data on Gemini EVA have demonstrated the inadequacy of space suit gas-flow cooling systems for sustained periods of high work rate. Metabolic rates during these activities ranged from resting to in excess of 3000 Btu/hr (ref. 5.16). The data showed that the actual work rates greatly surpassed those predicted, resulting in an overload of the gas cooling system. The crewman experienced a high perspiration rate, fatigue, and visor fogging during several of the Gemini EVAs. The Gemini gas cooling systems took advantage of the body's primary thermoregulatory mechanism of rejecting heat -- sweating. The use of this method accounted for approximately 75% evaporative and 25% convective heat removal. One significant problem arising from exclusive use of the gas cooling method is that man is physiologically unable to sweat enough to reject the consequent increase in body core heat at sustained high workloads.

The body is capable of storing various amounts of heat for as long as two hours without impairing safety or performance. This heat storage is of benefit to the EVA crewman, especially when using a gas cooling system. Recent studies show that men actively working in space suits can store up to 1000 Btu in actively working muscles without exceeding tolerance limits (ref. 5.17). NASA data have indicated a range of maximum allowable body heat storage from 440 to 660 Btu (ref. 5.18). Other investigators have obtained results which indicate both higher and lower allowable heat storage. Figure 5-15 shows the tolerance and general performance limits as a function of time and body heat storage (ref. 5.19).

Another limiting factor associated with gas cooling systems is the interaction of maximum gas cooling performance with limiting water loss (sweat) conditions. A water loss range of two to three percent of body weight is an accepted limiting condition for a typical 165 lb. crewman. This amount of water loss is generally accepted as resulting in fatigue for most subjects. Loss in excess of six percent results

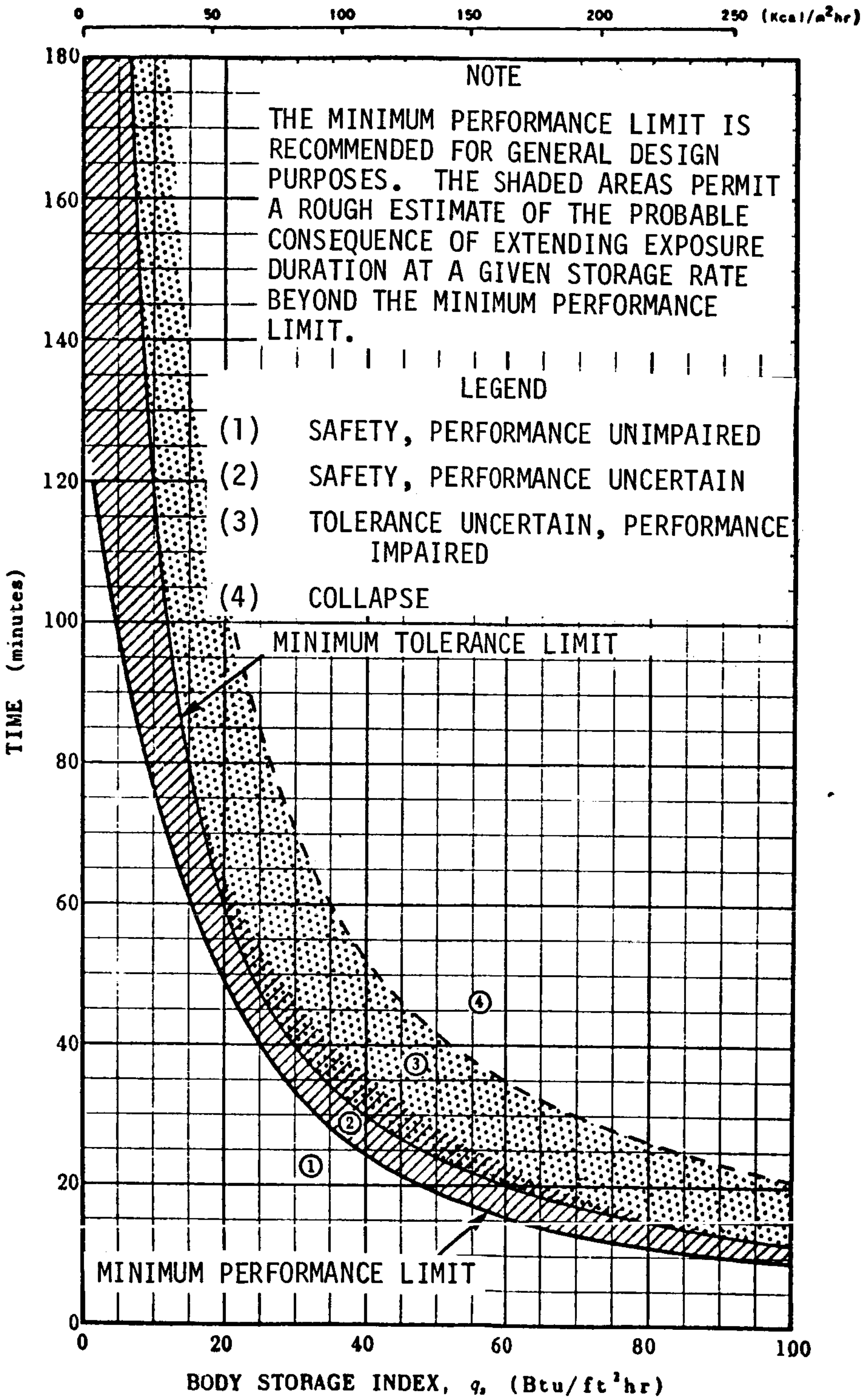


FIGURE 5-15: Thermal Performance and Tolerance Limits

in mental confusion, spastic muscles and deafness. A 15 to 20 percent loss results in death (ref. 5.16). Therefore, heat removal rates achieved with several gas cooling systems are adequate for the lower activity condition, but water loss limitations demonstrate the inadequacy of a gas cooling system for EVA missions. Figure 5-16 depicts the cooling capacity of an Apollo prototype (gas cooled) space suit as a function of flow rate at three internal suit pressures. The separation of cooling into sensible and latent loads is also shown. The latent load, a result of heat rejection through respiration and perspiration, is removed by evaporation. The sensible load, a result of heat being transported by means of blood flow from deep body tissues to the skin, is removed by convection. Although gas cooling systems may perform within water loss limits (Figure 5-17), there may be reasons (sweat rate, water loss, heat storage, etc.) for selecting a different system for EVA.

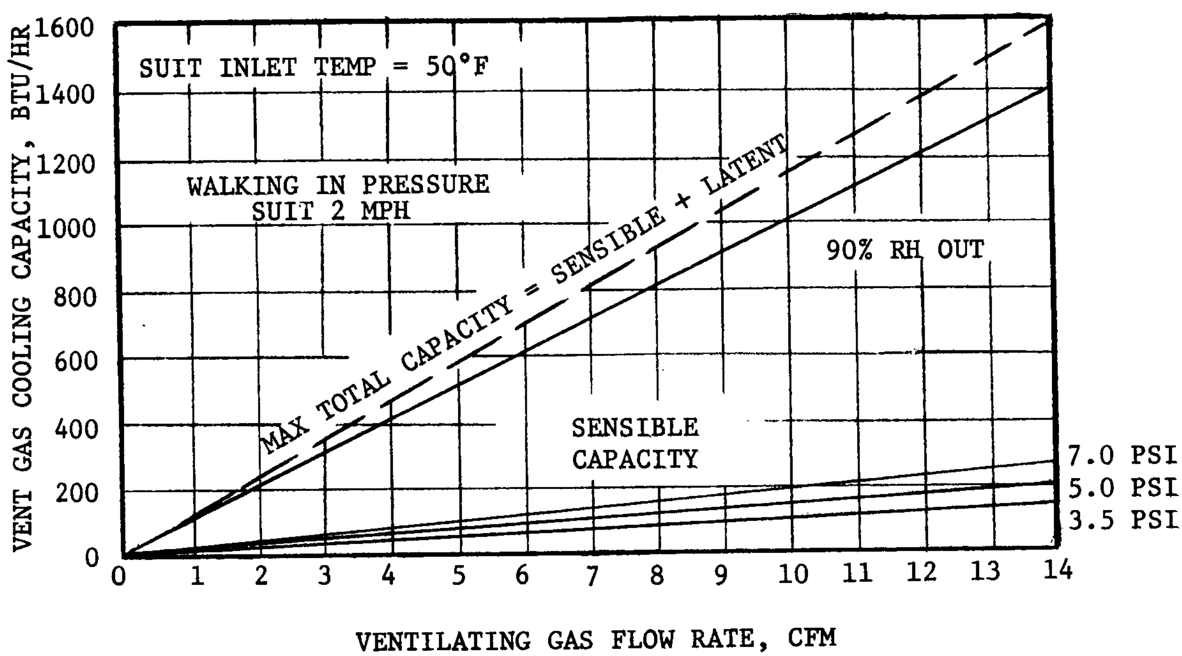


FIGURE 5-16: Pressure Suit Ventilating Gas Cooling

A gas cooled, A-7L series space suit is being used for the Apollo 15 - 17 transearth EVAs, since the workloads and task durations are relatively limited.

The use of liquid cooling garments (LCG) have been employed for all United States lunar EVA missions, for the Apollo 9 orbital EVA, and they are scheduled for use on the Skylab EVA missions. The liquid cooling garment consists of a loose mesh garment with a series of small flexible tubes sewn in. The tubes are placed in direct

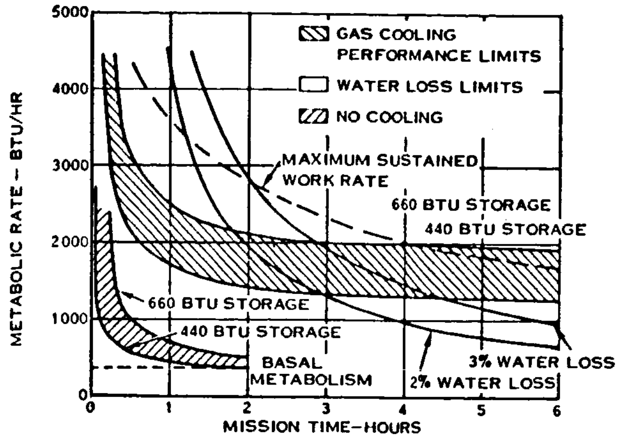


FIGURE 5-17: Water Loss Limits -- Gas Cooling System for a 165 lb. Crewman

contact with the crewman's skin when donned. Cool water is pumped through the tubes and absorbs the metabolic heat transported to the body's surface by the blood stream. As previously indicated, space suited missions requiring cooling in excess of evaporation by two to three percent of body weight (or another agreed-upon maximum weight loss) must use liquid cooling to preclude intolerable physiological stress. The LCG system must transfer from the body the amount of heat necessary to prevent excessive sweat loss by maintaining the skin temperature within certain limits to avoid triggering the body's active sweating mechanism (ref. 5.16).

The liquid cooling garment can also be used to apply heat to the crewman provided the liquid circulation system is properly equipped. The capability of heating the crewman, however, has not been a requirement on past United States EVA missions, nor is the need for it anticipated through the Skylab Program.

The LCG lower inlet temperature has been limited to 32°F to maintain crewman comfort and avoid the possibility of causing local frostbite. The upper limit is set at 113°F to avoid possible burns to the skin. Tests have been conducted to determine skin temperatures at which active sweating and shivering begin for various metabolic rates. Figure 5-18 depicts the LCG temperatures required to maintain a crewman within comfort thresholds. A liquid flow rate of 4.0 lbs/min was used. Figure 5-19 shows the same data as a function of metabolic rate for comparison purposes (ref. 5.16). Several manned tests were conducted in which the liquid flow rate through the LCG was varied during exercise. Results showed that heat removal at the same metabolic rate is largely independent of coolant flow rate. An overall heat transfer coefficient of approximately 42 Btu/hr/°F was calculated for flow rates of 2.0, 3.0 and 4.0 lb/min at a constant

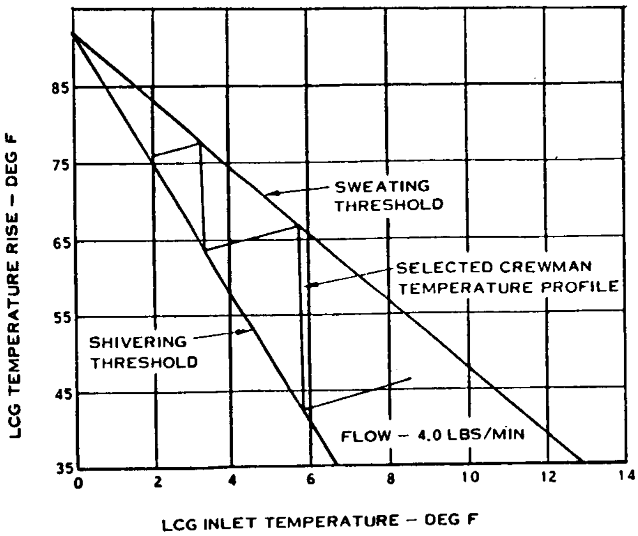


FIGURE 5-18: Subject Comfort Threshold Versus LCG Performance

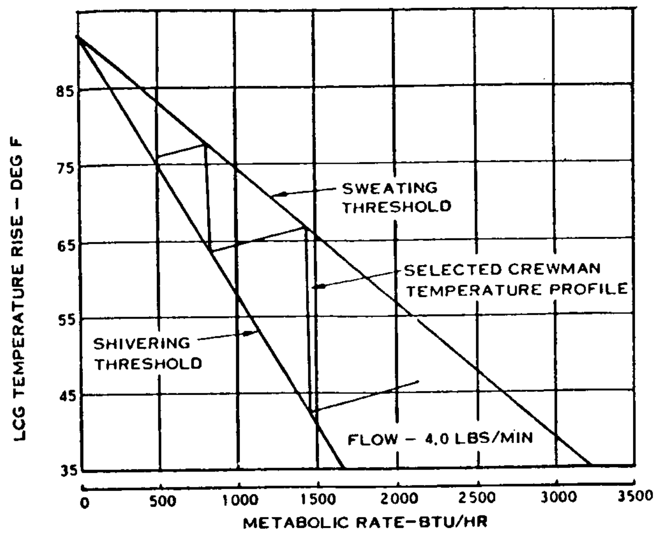


FIGURE 5-19: LCG Inlet Temperature Versus Metabolic Rate

inlet temperature of 45°F. Figure 5-20 shows LCG heat absorption versus metabolic rate when the flow rate was varied between 2.0 and 4.0 lb/min.

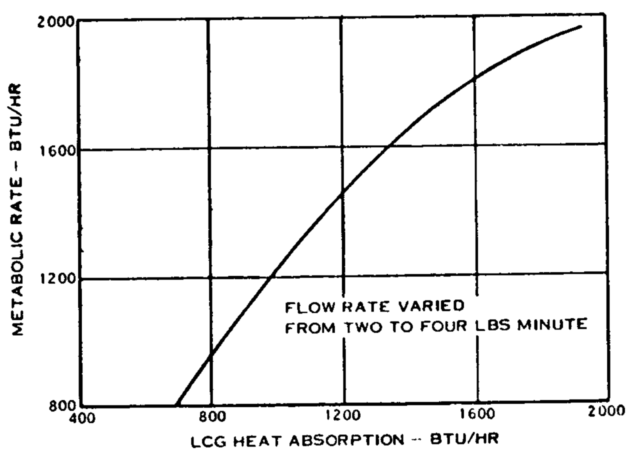


FIGURE 5-20: LCG Heat Absorption Versus Metabolic Rate

Current liquid cooling systems have demonstrated heat removal rates slightly above 2000 Btu/hr while maintaining the crewman below the sweating threshold. Metabolic rates in excess of 2000 Btu/hr require a liquid inlet temperature below skin comfort limits. Although the liquid cooling systems provide greater heat removal capacity, allowing higher work rates and longer duration missions, the requirements of a specific orbital EVA mission should dictate which physiological parameters should be emphasized in selecting a cooling system (ref. 5.16).

(5) Atmospheric Contamination

Trace Contaminants

Contaminants that can be generated either by construction materials, by equipment, or by the crewmen can constitute a major limitation on safety, habitability and mission duration. The state-of-the-art in environmental toxicology does not allow valid predictions of human tolerance to any toxic materials for periods of prolonged continuous exposure. Moreover, the mixture of several contaminants always carries the threat of synergistic potentiation. A given environment with a low barometric pressure, oxygen-rich atmosphere and the many physiologic and psychologic stresses which characterize the space environment combine to form a still unknown quantity which can influence man's resistance to chemical abuse. Because of the current uncertainties regarding spacecraft contamination data, few recommendations are made for continuous exposure to toxic trace contaminants other than those suggested by the National Academy of Sciences, National Research Council (NAS-NRC). The NAS-NRC's recommended contamination limits (1967) are contained in Appendix E.

Of the many construction/fabrication materials used in current spacecraft cabins, in space suits, and in environmental control systems, the groups of materials which are most likely to produce volatile contaminants are: (1) adhesives, (2) elastomers, (3) electrical insulation, (4) finishes, (5) coatings, paints and varnishes, (6) markings and inks, (7) foams, (8) greases and lubricants (9) moldings, (10) plastics and laminates, (11) potting and sealing compounds, and (12) thermoplastics. Categories of volatile products from these groups (both the major types and the most frequent sources) are listed in Table 5-3 (ref. 5.20).

The consideration of atmospheres for manned spaceflight must acknowledge all constituents present in trace amounts. Any trace contaminant assumes increased importance as mission duration increases and may or may not alter the crewman's response to a given atmosphere. This complicates the problem of determining acceptable threshold limit values for spacecraft toxicologic purposes. Laboratory tests of the Space Science Board, National Academy of Sciences, indicate that approximately 200 compounds have been identified in the Mercury, Gemini and spaceflight ground simulator atmospheres. Some 40 to 50

TABLE 5-3: Sources of Space Cabin Volatile Products

MAJOR TYPES OF GAS-OFF	TYPICAL SOURCES AND GAS-OFF PRODUCTS
Inorganics Alkanes Alkenes Alcohols Alkyl halides Aryl halides Benzene and homologues Carboxylic acids Aldehydes Ketones Aliphatic nitrogens Silicon compounds	Paints and coatings: Carbon monoxide Solvents Plasticizers Resins: Ammonia Ethylamine Silicone greases: Tetrachlorobenzene Polyurethane foams: Carbon dioxide Lubricants: Chlorine substituted fluorocarbons (up to C_6)

have occured in enough separate situations that their presence in the spacecraft should be suspected until they are proven nonexistent in that environment. Contaminants most frequently identified are listed in Table 5-4 (ref. 5.9).

As analytical techniques improve and new materials are developed, new compounds will certainly be added to the list and some older ones removed.

Those compounds which are due to man's presence can be expected to exist in the space cabin regardless of alterations in materials. These compounds are listed in Table 5-5. Numerous other compounds have been associated with man's presence, but these occur at sufficiently low production rates that they are not included in this listing. Because of the large number of materials and the uncertainties of their synergistic effects, cabin materials are usually screened by exposing animals to the gas-off products generated at 155°F (the highest normal operating temperature for most spacecraft components) in a 5 psia oxygen environment (ref. 5.9).

Several approaches were used to assure that compounds would not contaminate the Apollo atmosphere and reach levels toxic to the crewmen. Spacecraft cabin materials were selected on the basis of their off-gassing characteristics; animal toxicologic studies (mentioned above) were conducted, using off-gassed compounds from spacecraft materials; the atmospheres of various Apollo Command Modules

TABLE 5-4: Contaminants Frequently Detected in Space Cabins

COMPOUNDS	
Acetaldehyde	Ethylene
Acetic acid	Formaldehyde
Acetone	Fluorotrichloromethane
Ammonia	Hydrogen
Benzene	Hydrogen sulfide
n-Butane	Methane
2-Butanone	Methyl alcohol
n-Butyl alcohol	Methyl chloride
iso-Butyl alcohol	Methyl *iso*-butyl ketone
Carbon disulfide	Mestiylene
Carbon monoxide	*n*-octane
Chloroform	Pentane
Cyclohexane	*iso*-Pentane
1, 2-Dichloroethane	Propane
1, 1-Dichloroethylene	*n*-Propyl alcohol
Dichloromethane	*iso*-Propyl alcohol
2, 2-Dimethyl butane	Propylene
Ethane	Toluene
Ethyl acetate	1, 1, 1-Trichloroethane
Ethyl alcohol	Trichloroethylene
Xylene	Vinyl chloride

TABLE 5-5: Compounds Specifically Produced by Man

Carbon monoxide	Methanol
Hydrogen	Ethanol
Methane	Methyl ethyl ketone
Hydrogen sulfide	Acetic acid
Ammonia	Acetaldehyde
Acetone	Mercaptans

and Lunar Modules were analyzed for off-gassed compounds during altitude chamber tests at Cape Kennedy; and charcoal from the Apollo spacecraft environmental control systems was analyzed post-flight (ref. 5.9).

Although approximately fifty compounds have been identified in spacecraft cabin atmospheres, their concentrations have been too low to be of toxicologic significance, even after the compounds were grouped according to their primary modes of action. Of particular importance, however, was the presence of relatively large concentrations of halocarbons, such as methanol, ethanol, proponol, isoproponol, methyl chloride, mestiylene and *n*-octane. Since halocarbons can react with the carbon dioxide absorbing lithium hydroxide to produce highly toxic compounds, efforts should be taken to closely control the halocarbon concentrations in future spacecraft cabin atmospheres (ref. 5.7). In preparation for the Mercury and Gemini Programs, candidate cabin materials were heated for a period of time in a closed chamber under 5 psia oxygen and were subjected to an odor test by a panel of selected individuals. If the odor test produced a sufficiently low cumulative score, the material was acceptable for use in the spacecraft cabin. Special studies conducted during the early Apollo Program showed that man is a very good sensor for ethylene glycol toxic agent (ref. 5.21).

A very minor degree of methaemoglobinaemia was observed in the Apollo crewmen postflight. A review of the contaminants in the spacecraft cabin atmosphere did not identify the cause.

Water Vapor

Humidity control and water vapor removal in the spacecraft and space suit atmosphere are important considerations from the aspects of crewman comfort, condensing nuclei for toxic gases, electronic equipment operation and condensation within/upon spacecraft equipment. (The cabin relative humidity is limited to 40 to 70 percent on current spacecraft under nominal conditions.) Water vapor diffusivity of the spacecraft cabin or space suit atmosphere has an important effect on evaporative cooling. Insensible water loss through the crewman's skin will be greatly accelerated in the rarified, low pressure atmosphere of 5 to 7 psia than would be the case at sea level. Present data indicate that for the 5 to 7 psia region, with skin temperature in the comfort zone, the insensible water loss increase is probably about 30% over that at ground level (30 ml/hr/man). Crew comfort, potable water supplies, and spacecraft environmental control systems may be affected by this increase (ref. 5.16).

In considering toxic atmospheric hazards for prolonged periods, the crewman must be concerned with the fact that vapor particles can act as condensing nuclei for toxic gases. This facilitates these contaminants' entrance into the lower respiratory tract, since in the normal earth atmosphere, because of their high water solubility, they

are generally trapped in the upper respiratory tract. Those which reach the lower respiratory tract are rapidly absorbed into the bloodstream, and a toxicologic effect may occur in a short period of time.

Unless water vapor is controlled in the spacecraft atmosphere, the relative humidity increases until conditions become unpleasantly humid, odors increase and water condensation (depending on wall temperature) can occur. An example of water condensation problems might be condensation in an aluminum canister containing sodium superoxide, causing the generation of sodium hydroxide, which generates hydrogen from aluminum contact, etc. (ref. 5.20). High humidity can also be the basis of numerous problems and malfunctions associated with spacecraft electrical and electronic equipment. Problems of this nature, however, are too great in number to allow for extensive discussion in this document.

Excess moisture generated in the Apollo cabin and suit circuits is removed by a water separator (located in the suit circuit) and is transferred by a cyclic accumulator to the waste-water stowage location for subsequent use as an expendable coolant. The cyclic accumulator actuates automatically every ten minutes with a removal capacity of 130 cc water per actuation. The Apollo cabin and suit environmental control systems are integrated, however, when the crewman is in the space suit mode and is isolated from the spacecraft cabin atmosphere. The ventilating gas flow leaving the space suit passes through a debris trap which removes particles larger than 0.04 inch. The ventilation gas then passes through two parallel elements of lithium hydroxide and activated charcoal, where control of carbon dioxide and odor for the cabin (Command Module) and space suits is accomplished. A schematic of the Apollo environmental control system is shown in Figure 5-21 (ref. 5.10).

Odor in Spacecraft and Space Suit Atmospheres

The human olfactory sense permits detection of vapors of many organic substances at concentrations of 10^{11} to 10^{13} molecules/cm^3 of air and of some at concentrations as low as 2×10^9 molecules/cm^3. Fortunately, the human olfactory sense adapts to odors quite rapidly. Experience in spacecraft and space suits suggests that crews are not bothered by odors in the atmosphere which may overwhelm new additions to the crew. Offensive odors were detected in the Apollo 9 and 11 spacecraft; however, their cause, nature, and potential effects have not been totally determined.

Microbial Contaminants

The microbial flora of the space cabin and space suit represent particulate contaminants that can have significant effects on future long duration spaceflight, both on man and equipment. The crewman is, of course, the major source of microbes in the closed environment. Current spacecraft, with their limited volume and hygienic

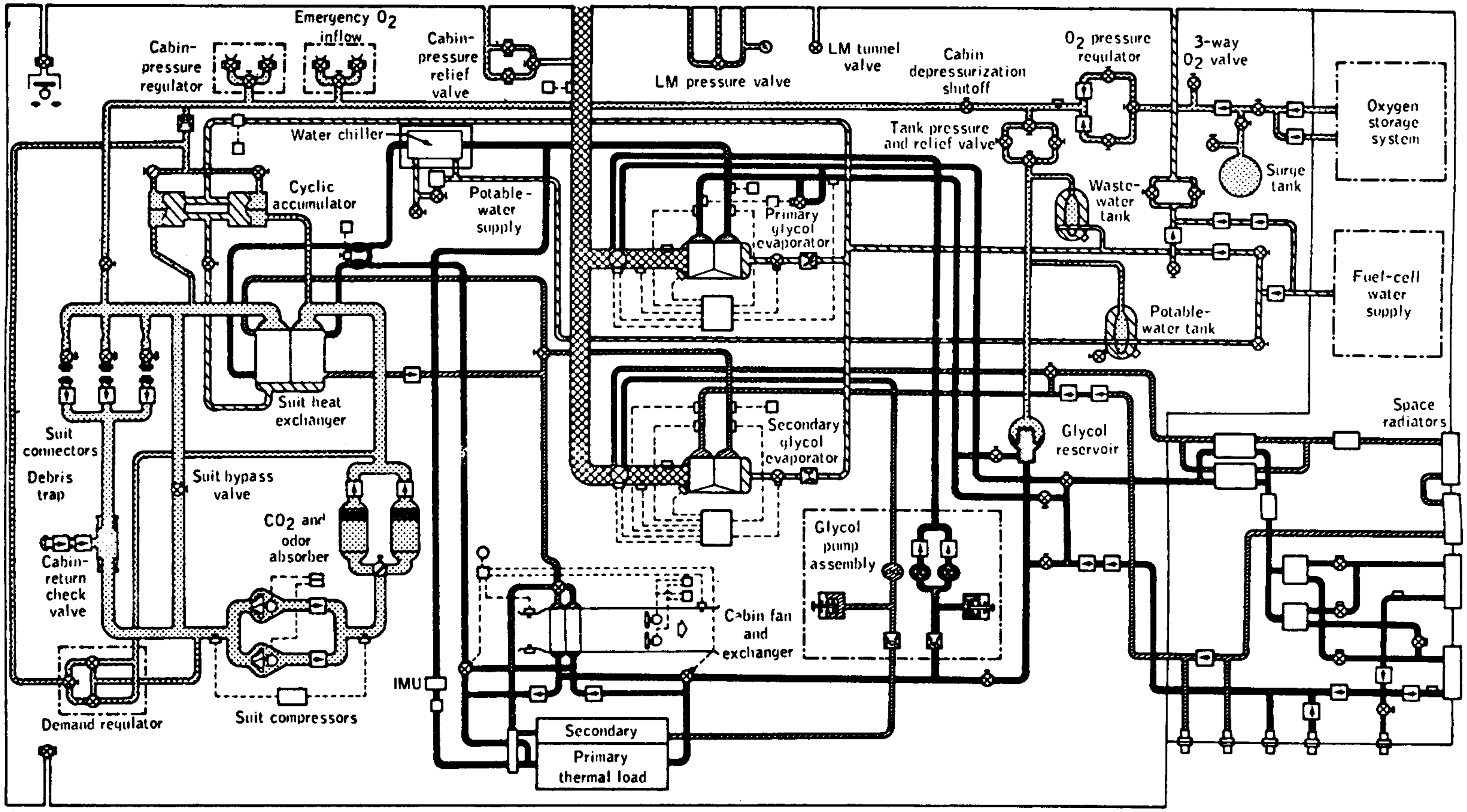


FIGURE 5-21: Apollo Environmental Control System

facilities, increase the problem of bacteria control. Studies conducted in sealed cabins indicate an increase in the total skin flora, especially in axillary, groin, and other fold areas. This tendency is again increased by the wearing of a space suit and by high humidity. The buildup tends to reach a plateau after variable periods of time in a given environmental situation. In space suits in 100% oxygen with minimum hygienic procedures, the bacteria count of the body reaches a maximum in about one week and remains elevated or declines thereafter.

No microorganism with unfamiliar morphological structures or unusual physiological responses have been detected in microbiological analyses following the Apollo missions. Neither the preflight nor postflight phases of the missions were impaired by the occurrence of viral illnesses in the crewmembers. Data bits on some 4000 microorganisms have been collected during the Apollo missions. Certain consistent findings may be indicative of biological trends in the analyses to date. The appearance of certain organisms only during the postflight sampling interval suggests that microbial shifts may favor the growth of opportunist organisms. In addition, certain other components of the normal flora have been isolated from aberrant sites. Taken together, these observations suggest that microflora changes occuring in the spacecraft environment may not be compatible with man's health and well-being during missions of extended duration. Further study is needed in these areas (ref. 5.6).

Contamination Removal Techniques

The presence of the many contaminants, the degree of uncertainty regarding the rate of production, and the concern regarding continuous exposure limits of man to these compounds require preventive action to ensure that contamination of the atmosphere does not limit mission success or duration. Such action embodies at least two approaches: (1) controlling the entry of materials into the spacecraft, and (2) devising techniques to remove contaminants from the atmosphere. The first approach can be influenced somewhat by the careful selection of materials within the spacecraft and "modified-isolation" of the crewmembers during preflight periods.

Several approaches may be utilized to remove contaminants from the sealed environment. These include leakage, physical adsorption, chemical absorption, and chemical or catalytic conversion of controllable compounds to nontoxic form. The passive use of leakage, although simple and reliable, will be of little use in long duration space missions due to the need to conserve atmospheric material by minimizing or eliminating routine leakage. Regenerable adsorbers and catalytic oxidation probably will be the main approaches in control of contaminants in prolonged future spaceflights. The regenerable adsorbers function by adsorbing the material on their surface until it becomes fully loaded, with higher molecular weight compounds being adsorbed more efficiently than those of lower molecular weight. The catalytic oxidizer functions by passing the contaminant over a

catalyst (usually heated) and converts the material to carbon dioxide (in the case of carbon monoxide), to water (in the case of hydrogen), and carbon dioxide plus water (in the case of most hydrocarbons). The main point of concern in the use of catalytic oxidation is the possible formation of degradation products significantly more toxic than the compound being removed. Examples of this include the formation of hydrochloric acid from chlorinated hydrocarbons, hydrofluoric acid from fluorinated hydrocarbons, and dichloracetylene from trichloroethylene.

It is apparent that positive control of materials and contaminant removal techniques must be coupled with a means of contaminant detection if a high degree of assurance regarding the quality of the environment is required. Such techniques designed to be used in spacecraft are becoming available and should be considered as an integral part of environmental control systems of the future (ref. 5.9).

5.2.3.2 Prebreathing Requirements

Preventing dysbarism, or decompression sickness, from occurring in spaceflight is of major significance prior to vehicle launch and during pressure and atmosphere composition changes made in flight. The total range of possible pressure exposure of a spaceflight crew in any current spacecraft atmospheric system is from near sea level to the lowest space suit design pressure. The space suit low point (3.7 psia) was chosen to maintain a sea level equivalent of oxygen in the lungs while minimizing the effects of differential pressure on space suit mobility. Since exposure to the 3.7 psia space suit atmosphere could be reached in an emergency immediately after leaving the earth's atmosphere during launch, the associated levels of decompression sickness can never be completely avoided (ref. 5.22). They can, however, be minimized by such measures as denitrogenation prior to and during launch. Reduction in cabin pressure to 5 psia and a further reduction to 3.7 psia in the space suit during orbital EVA required that the crewmen on the Mercury and Gemini flights receive two hours of denitrogenation before flight by breathing 100% oxygen. Coupled with the further denitrogenation accomplished in the spacecraft, this proved to be ample protection from hypoxia and dysbarism. Additional chamber studies following the Gemini program showed that a minimum of 3 hours of denitrogenation is necessary to provide the best protection against decompression sickness. Therefore, Apollo crews have prebreathed for a 3 hour period on 100% oxygen, including time on the launch pad. Once the cabin has reached 5 psia with the 60/40 atmosphere, the crewmen are still protected against decompression sickness when breathing this atmosphere, provided they have been adequately denitrogenated preflight. This method has prevented the development of decompression sickness on any mission thus far (ref. 5.6).

The 14.7 psia, 100% oxygen exposure prior to launch and the 5 psia mixed gas atmosphere on-orbit still carries with it a demonstrable risk of either decompression sickness in some form during the exposure or the initiating of asymptomatic bubble formation which predisposes the crewmen to dysbarism symptoms on exposure to any lower pressure during the lifetime of such silent

bubbles. Tissue nitrogen wash-out, unlike that of plasma nitrogen, is often difficult to predict. Some tissues with greatly variable arterial perfusion rates (testes, spleen) may retain the major portion of tissue-dissolved nitrogen even after 4 hours of denitrogenation (ref. 5.23). Decreased perfusion may be due to arteriolar and capillary contraction caused by the higher tissue oxygen tension during pure oxygen breathing. Since future U. S. spacecraft cabin atmospheres may consist of a two gas system at pressures of 7 to 14.7 psia, use of inert gases has been investigated extensively in ground space-flight simulation chambers. In these tests, the assumption was made that the crewmen, after denitrogenation at ground level and breathing oxygen through aviator's masks for 4 hours, would enter a cabin atmosphere of pure oxygen at 5 psia. After 2 1/2 hours, the pressure was decreased to 3.5 psia, marking the donning of a pressure suit. Under this condition 5 deep knee bends and 5 push-ups were performed at 5-minute intervals, simulating the exertion of transfer into another "orbiting" cabin atmosphere of 46% oxygen - 54% nitrogen at 7 psia. This exposure was extended from 4 to 12 hours followed by another decrease to a 3.5 psia space suit atmosphere and finally recompressed back to normal ground pressure. Bends did occur subsequent to exposure to 3.5 psia. The return to 7 psia compared to 5 psia showed a markedly better protective effect (4 cases of bends compared with 11 cases, respectively). Other results show that age and physique have generally slight influence on susceptibility to bends. Bends, once started, tended to increase in subsequent stages of the same flight. Almost 90% of the symptoms were referred to knee or knee and ankle joints. An interesting approach to determine the amount of dissolved nitrogen in venous blood was made by using chromatographic techniques in very small samples of blood. Figure 5-22 shows the elimination and reaccumulation of dissolved nitrogen caused by various exposure times to different atmospheres. This determination of the changing amount of nitrogen in venous blood, as a function of time, permits an estimation of the time required for breathing oxygen prior to going to a lower pressure and then engaging in exercise. Subjects having a greater than average fat/lean ratio (greater than 0.3) generally had a significantly higher bends incidence (ref. 5.24).

Accidental inhalation of a few breaths of air during or at the termination of prolonged denitrogenation does not appear to offer an appreciable threat of decompression sickness. The small volume of acquired nitrogen, dissolved in the plasma, would be expected to wash out in about 10 minutes with resumption of breathing oxygen (ref. 5.23).

Although these results cannot be regarded as final, they nevertheless provide a valuable guide to the direction in which trials on cabin atmospheres for spacecraft should continue. Practical experience under real flight conditions has just started to be accumulated. Berry (ref. 5.6) points out that the Apollo spacecraft had, before and at launch, an atmosphere of approximately 64% oxygen and 36% nitrogen (to minimize fire hazard), while the crew was denitrogenated 3 hours prelaunch with pure oxygen. Both hypoxia and dysbarism were thus avoided.

United States' space missions in the planning stage currently envision mixed-gas atmospheres, primarily oxygen/nitrogen, in the 7.34 to 14.7 psia range. Space suits with operational pressures of 7 to 8 psia are presently

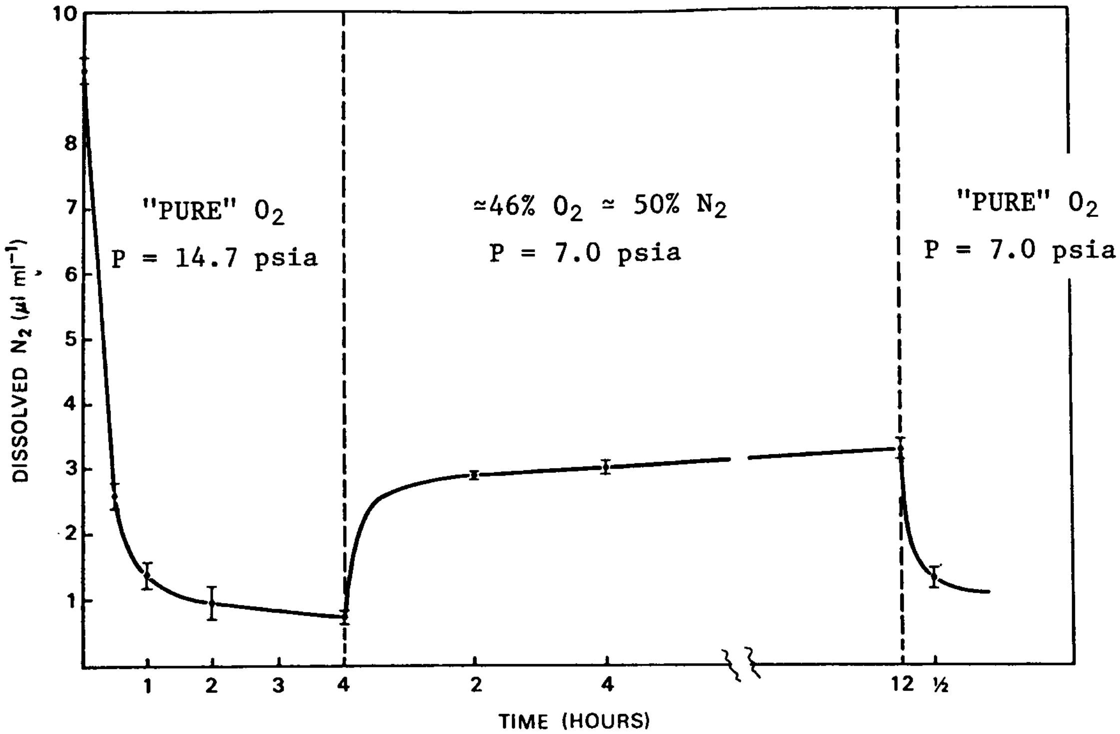


FIGURE 5-22: Elimination and Reaccumulation of Nitrogen in Venous Blood

being designed and tested. Also studies are currently being conducted for on-orbit rendezvous of U. S. spacecraft (5 psia, oxygen) with spacecraft of 14.7 psia mixed-gas atmospheres (approximately 20% oxygen and 80% nitrogen). Prebreathing (denitrogenation) requirements associated with transferring between each of these atmospheric environments must be considered in future space programs. Table 5-6 presents the general NASA-accepted prebreathing times (100% oxygen) required for most atmospheric transfers. In each of the cases, the crewman is assumed to have "stabilized" with respect to denitrogenation in the previous atmosphere.

5.2.3.3 Radiation and Micrometeoroid Protection

(1) Radiation Characteristics

One of the hazards inherent in extravehicular activity is the effect of radiation on the EVA crewman. Information provided in the following paragraphs summarizes known data on the orbital environment with regard to ionizing particle radiation and magnetic fields and provides recommendations on exposure limitations. These data should provide an indication of the parameters requiring attention in planning EVA such that the crewman is protected. The information used is drawn from areas other than EVA, because of the small amount of EVA data

TABLE 5-6: General NASA-Accepted Prebreathing Times

TRANSFER FROM	TRANSFER TO	REQ'D. TIME (Hours)	REMARKS
14.7 psia (3.2 ppO_2)	8.0 psia (100% O_2)	0	
14.7 psia (3.2 ppO_2)	8.0 psia (3.5 ppO_2)	0	
14.7 psia (3.2 ppO_2)	5.0 psia (100% O_2)	3	Condition for Russian/U.S. transfer
14.7 psia (3.2 ppO_2)	5.0 psia (100% O_2)	3	Condition at current U.S. launch
14.7 psia (3.2 ppO_2)	3.7 psia (100% O_2)	4	
8.0 psia (3.5 ppO_2)	3.7 psia (100% O_2)	1-2*	
8.0 psia (3.5 ppO_2)	5.0 psia (100% O_2)	1-2*	
5.0 psia (100% O_2)	14.7 psia (3.2 ppO_2)	0	Condition at current U.S. reentry and Russian/U.S. transfer
5.0 psia ($\approx$100% O_2)	3.7 psia (100% O_2)	(TBD)	Condition at orbital U.S. EVA
5.0 psia (3.5 ppO_2)	3.7 psia (100% O_2)	(TBD)	

*This condition requires additional testing.

available and because man's response to EVA-incurred radiation is interdependent on exposures preceding and following EVA.

Types of Space Radiation

Ionizing radiation in space can be classified into three categories: (1) primary galactic cosmic radiation, (2) geomagnetically trapped radiation, and (3) solar flare and solar wind radiation. Such radiation occurs naturally in the space environment, although trapped radiation does include electrons resulting from high altitude nuclear explosions. In addition to these three categories of primary radiation, secondary radiation (produced by interaction of primary particles with construction elements and other materials of the spacecraft, with the space suit, and with superficial biological tissue) should be considered during spaceflight. Also the use of nuclear propulsion of future spacecraft may pose additional radiation protection problems for the EVA crewman (ref. 5.25). The basic terms for expressing the exposure field and the absorbed dose of radiation are seen in Figure 5-23.

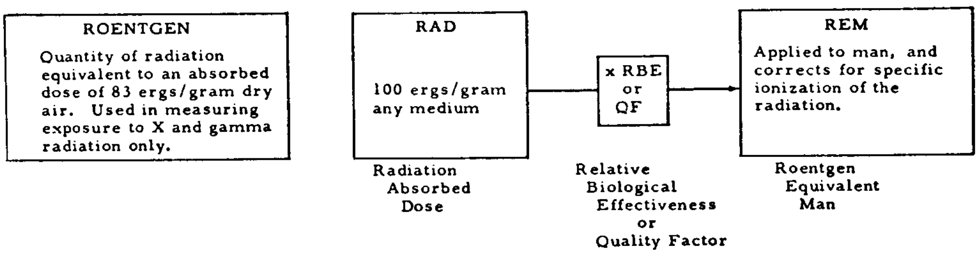


FIGURE 5-23: Radiation Terms

Primary galactic cosmic radiation is believed to originate from galactic space. It consists of atomic nuclei which are stripped of all their electrons and which have been accelerated in turbulent interstellar magnetic fields. The composition of cosmic radiation at the top of the earth's atmosphere approximates 85% protons, 12% helium nuclei, and 1% nuclei of the carbon nitrogen-oxygen group. Occurring less frequently in cosmic radiation are heavy primaries with electromagnetic charges up to that of iron, lithium, beryllium, and boron. In addition, there is evidence of high energy electrons and high energy gamma rays. Energy levels from cosmic radiation range from 10^9 to 10^{18} ev (electron volts) (ref. 5.26).

Geomagnetically trapped radiation exists as two large belts around the earth (commonly known as the Van Allen Belts) which have a higher

radiation flux than in surrounding space. The belts, of which the innermost has its intensity maximum at 1.5 earth radii (from earth center) and the outermost at 5 earth radii, consist of charged particles trapped in the earth's magnetic field. These two primary belts are made up of six discrete energy belts: two large electron belts separated by a large slot, one high energy proton belt, and three belts consisting of low energy protons. Energy levels range up to approximately 10^3 mev (million electron volts) for the high energy protons. In general, the sharp rise in radiation level is first found at 1.16 earth radii (about 1,000 km altitude above sea level). At magnetic field mirror points, however, the inner belt of protons dips down to as low as about 200 km, creating the so-called South Atlantic Anomaly. A graphic representation of the Van Allen Belts is shown in Figure 5-24.

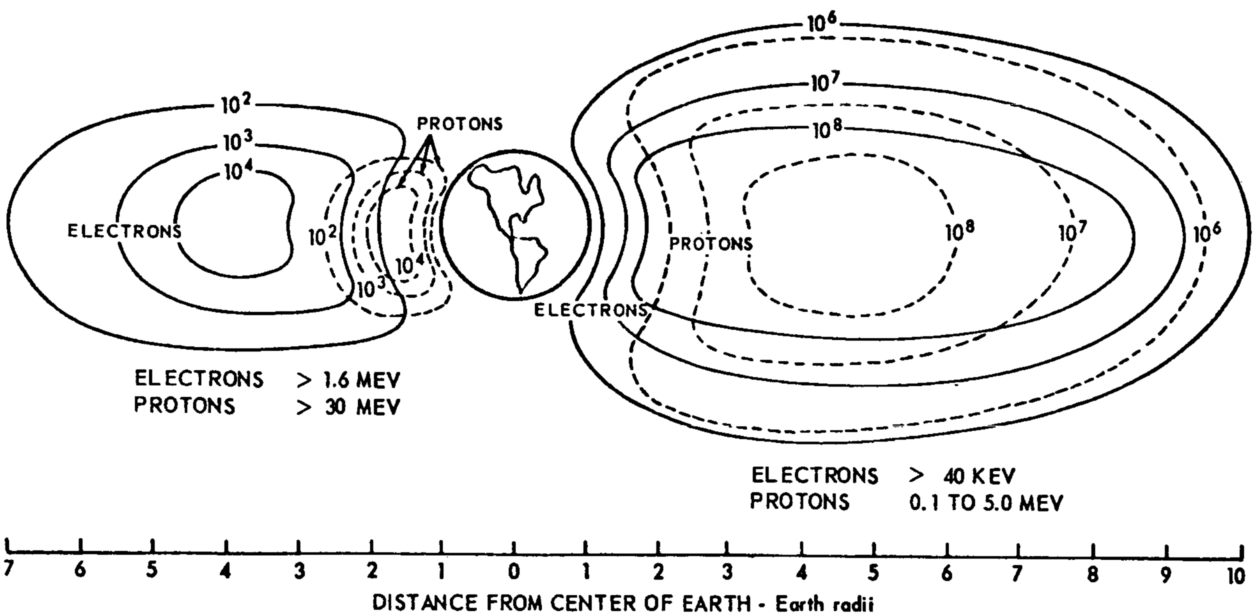


FIGURE 5-24: Radiation Trapped in the Earth's Magnetic Field, Known as the "Van Allen Belts"

Radiation from solar flares, solar wind, and corpuscular streams originates with the normal activity of our sun. Solar wind, consisting of magnetic fields and low energy particles, is a constant, perpetual outflow from the solar corona and is not believed to be a significant human hazard. Solar corpuscular streams, lasting for weeks or months, emanate intermittently from the sun. The spiral streams interact with solar wind and galactic radiation, and the particles which compose the streams (while probably of low significance by themselves) add to the radiation levels entrapped in the Van Allen Belts. Of much greater significance are the particle

fluxes ejected from solar flares. Very small flares, which are of no importance to spaceflight, occur each day. Moderate and large flares are less frequent, and giant solar flares occur only a few times in many years. During peak solar activity, which occurs every eleven years, from five to thirteen eruptions causing high energy solar proton events of up to a few hours duration may be seen over about a year of such activity.

In addition to protons, solar flares also release radio frequency waves, soft X-rays, electrons, alpha particles, ionized gas clouds, and light in the visible and ultraviolet parts of the spectum. The first protons arrive in the vicinity of the earth from 5 to 20 minutes after optical and radio emissions have been received, with the bulk of the proton shower arriving later. The total energy incident on the top of the earth's atmosphere following a major flare event is about the same order of magnitude as the total energy that the galactic cosmic radiation delivers in a year's time (ref. 5.26). It is not possible, at present, to classify the flare events with regard to radiation hazards, since both the instantaneous dose rate and the spectral configuration are highly variable during a single event. Progress is being made toward predicting the occurrence of flares. Maximum warning at present of a definite flare event is on the order of 10 to 15 minutes. This should allow sufficient time for the return of an orbital EVA crewman to the relative safety of his space vehicle.

Radiation Safety Criteria

In radiological practice, a permissible dose of irradiation for man has been defined as follows: "It is a dose accumulated over a long period of time or obtained as the result of a single irradiation which, in light of modern concepts, is associated with an insignificant probability of somatic or genetic damage. It is a dose for which the traceable effects of irradiation are generally less pronounced than would be considered unacceptable both by the irradiated man himself and by competent medical specialists." (ref. 5.27)

The concept of a permissible dose applicable to spaceflight can be more reasonably identified and interpreted by use of the Space Science Board's review of Radiobiological Factors in Manned Space Flight. The Space Science Board's approach recognized the limits of the available data, indicated deficiencies in our knowledge, and clearly left the user with the responsibility for developing and justifying his own standards, based upon the unique operating problems of each given space mission. Thus, there is no single set of "permissible dose" values, but, rather, there is the caution to balance the risk of radiation exposure against the scientific gains anticipated for each particular mission. Therefore, the development of radiation dose criteria should be approached with the full knowledge that there is some finite risk involved. Certain general considerations concerning the man should be viewed. These include the following points (ref. 5.28):

- Biological variability among different individuals can be a factor of 2 in terms of dose response (i.e., 200 rads may produce a dose response similar to that of 100 rads in one person while another individual with the same 200 rad dose may respond as if he had received 400 rads).

- Biological effects of radiation are a function of dose, dose rate, energy, and the type of radiation.

- Dose protraction, fractionation, recovery rates, and residual damage modify radiation response.

- There are acute and delayed effects to consider that are of both somatic (the exposed person) and genetic (progeny) interest.

For future manned space missions, realistic radiation safety criteria should be established, and agreement on a "biologically acceptable dose" reached. This "acceptable dose" should be based on criteria other than those used for setting the maximum permissible dose in radiological work. This would be justified, since the dose received in future spaceflight will probably be a once or twice in a lifetime exposure for selected crewmen. Some medical specialists think that, under these circumstances, the acceptable dose could be quite high. Alexander and Rosen recommend 50 rad as a tolerance limit for one time radiation doses. Such a dose of radiation can apparently be tolerated repeatedly if at least one week passes between the exposure. In the opinion of Langham, a dose of 100 rad at one time can be regarded as permissible. Baum and Hazel (ref. 5.27) maintain an even bolder view. In their opinion, a dose of the order of 125 rad can be acceptable. They also believe the irradiation with 100 rad can be repeated at intervals of 120 days.

Purser, Faget and Smith (ref. 5.29) have prepared a table of expected effects from one time radiation doses as a function of dose strength (Table 5-7).

In the time frame of future space missions (Skylab, 56 days on-orbit) the pertinent radiation symptoms could be malaise, nausea, vomiting, erythema, iritis, epilation, oropharyngeal lesions, gingivitis, hemorrhage, diarrhea, bloody diarrhea, fever, and hematologic depression as demonstrated by a change in lymphocytes at 2 to 3 days; a drop in platelets at about 3 weeks; and a drop in neutrophils at about 5 weeks (Figure 5-25). The time course with respect to dose can be reasonably identified as a guide to specific mission planning (Figure 5-26).

On the basis of these relationships (effects versus dose and time of onset), specific mission profiles can be discussed against the radiation environment, possible sequelae, and the doses required for such cases (ref. 5.28).

TABLE 5-7: Expected Effects From Acute Whole-Body Radiation

Dose in Rads	Probable Effect
0 to 50	No obvious effect, except, possibly, minor blood changes and anorexia.
50 to 100	Vomiting and nausea for about 1 day in 10 to 20% of exposed personnel. Fatigue, but no serious disability. Transient reduction in lymphocytes and neutrophils.
100 to 200	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in up to 50% of personnel; < 5% deaths anticipated. A reduction of approximately 50% in lymphocytes and neutrophils will occur.
200 to 350	Vomiting and nausea in 50 to 90% of personnel on first day, followed by other symptoms of radiation sickness, e.g., loss of appetite, diarrhea, minor hemorrhage; 5 to 90% deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months.
350 to 550	Vomiting and nausea in most personnel on first day, followed by other symptoms of radiation sickness, e.g., fever, hemorrhage, diarrhea, emaciation. Over 90% deaths within 1 month; survivors convalescent for about 6 months.
550 to 750	Vomiting and nausea, or at least nausea, in all personnel within four hours from exposure, followed by severe symptoms of radiation sickness, as above. Up to 100% deaths; few survivors convalescent for about six months.
1000	Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness.
5000	Incapacitation almost immediately (several hours). All personnel will be fatalities within one week.

For missions of 60 days or less in orbits below 200 nautical miles (NM), a crewman will receive about 25 rad, which in this case will be of moderately low energy. Furthermore, since this is a superficial dose of radiation, he will not see the symptoms of malaise, anorexia, nausea, vomiting, diarrhea, erythema or epilation for reasons of dose versus effect. Similarly, it would not be possible to measure the usual hematologic response, other than perhaps very subtle changes presumed to be associated with low doses of ionizing radiation (i.e., chromosome aberrations). Whether or not long-term delayed effects would ever be manifested with such doses would be based solely on the statistical and/or actuarial predictions of the present. It is questionable if there are any human data to substantiate an increased incidence of leukemia and/or a shortening of life span at this low dose (25 rad). Similarly, such dose levels are well below cataracto-genic dose limits. Variable dose rates, nonuniformity of dose, little depth of penetration, dose protraction, the quality factor

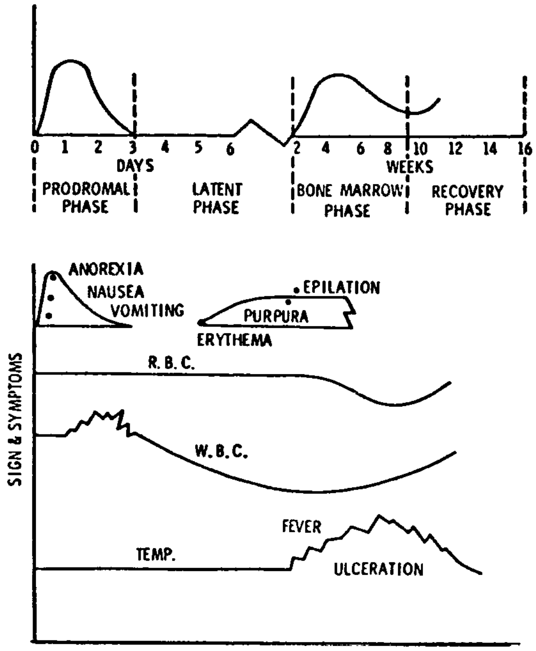
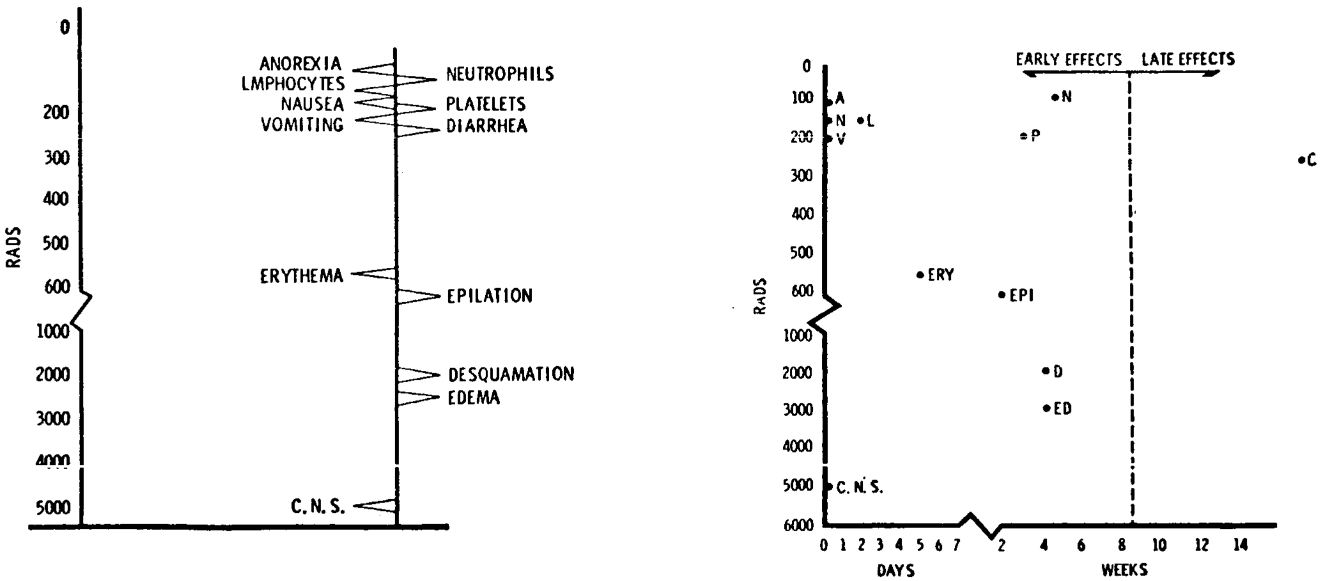


FIGURE 5-25: Phases of the Acute Radiation Syndrome



LEGEND: In "Days" section: A--Anorexia, N--Nausea, L--Lymphocytes, V--Vomiting, ERY--Erythema; In "Weeks" section: N--Neutrophils, P--Platelets, C--Cataracts after 16 weeks, EPI--Epilation, D--Desquamation, ED--Edema.

FIGURE 5-26: Acute Effects vs Dose vs Time of Onset

one would apply to the low energy protons, and the beta particles in the South Atlantic Anomaly all tend to reduce the effective radiation dose values. This same argument holds for higher circular orbits up to stay times of 60 days. For circular orbits up to one year's duration, it would be necessary after the exact orbit has been established to exercise caution for reasons of possible skin effects. In all likelihood, the protraction and fractionation of dose again would tend to discount even this effect, except for the long term delayed situation (several years postradiation). Here it is possible, though not very probable, that skin cancers could form, but the region for this concern is at present higher than altitudes being planned for most future missions.

The validity of the above, however, must be prefaced by the following qualifying conditions: EVAs must be properly programmed; no particles may be added to the anomaly from high altitude nuclear testing; and orbital altitudes may not be changed upward, i.e., 400 to 500 NM, for many days. As the orbit goes up in altitude, (i.e., 400 to 500 NM), there is sufficient time spent in the more intense region of the anomaly and the fringes of the inner Van Allen belt to markedly increase exposure to the skin. In this specific case, a skin dose could accumulate to produce mild transient erythema and, as a consequence, slight discomfort. Slight differences in shielding, even to the degree of protection afforded by a partial body shield (i.e., radiology aprons and water-cooled undergarments) could make a difference. This is not only true for the primary dose but equally true for some of the secondaries produced from electrons (ref. 5.28).

NASA Recommended Dose Limits

Radiation dose limits currently recommended by NASA for the American manned spaceflight program are listed in Table 5-8. It has been noted that these "maximum permissible doses" are probably on the conservative side, when the effect such doses would have on crewman performance and consequently on the safety of the mission is taken into consideration (ref. 5.25).

Radiation Doses on Past U.S. Missions

In the Mercury project (only in flights MA-8 and MA-9), the South Atlantic Anomaly and the artificial electron belt created by the Starfish nuclear explosion test called for a close look at the radiation problem. However, the calculated daily radiation dose was only 16 mrad to the skin and 200 mrad to the eyes. The doses were confirmed by in-flight measurements.

The Gemini flights generally did not reach an altitude involving the Van Allen Belts, but they did pass through the South Atlantic Anomaly. The onboard radiation measuring system and the personal dosimeters on the crewmembers confirmed that the environment was at the lower end of the calculated range. In a 60 nautical mile orbit, crews received

TABLE 5-8: Radiation Exposure Dose Limits Currently Recommended by the National Aeronautics and Space Administration (ref. 5.30)

Critical organ	Maximum permissible integrated dose (rem)	RBE (rem/rad)	Average yearly dose (rad)	Maximum permissible single acute emergency exposure, protons only (rad)	Maximum permissible single acute emergency exposure, alpha particles and protons (rem)
Skin of whole body	1600	1.4 (approx.)	250	500*	700*
Blood-forming tissues	270	1.0	55	200	200
Feet, ankles and hands	4000	1.4	550	700**	980**
Eyes	270	2***	27	100	200

* Based on skin erythema level.

** Based on skin erythema level; however, these appendages are believed to be less radiosensitive.

*** Slightly higher RBE assumed since eyes are believed more radiosensitive.

approximately 15 millirads per 24 hours in the Gemini Program. The total doses received on the Gemini flights are presented in Table 5-9.

TABLE 5-9: Radiation Doses on Gemini Missions

Mission	Duration	Mean Cumulative Dose	
		Command pilot	Pilot
	hr:min	mrad	mrad
III	4:52	<20	42 ± 15
IV	96:56	42 ± 4.5	50 ± 4.5
V	190:56	182 ± 18.5	170 ± 17
VIA	330:35	25 ± 2	27 ± 2
VIII	25:53	155 ± 9	170 ± 10
VIII	10:41	<10	10
IXA	73:04	17 ± 1	22 ± 1
X	70:46	670 ± 6	765 ± 10
XI	71:17	29 ± 1	26 ± 1
XII	94:37	<20	<20

The Apollo 8 flight was the first to leave earth orbit and traverse the Van Allen Belts, both on translunar and transearth coast. Since the solar flare network is valuable in helping to predict solar events, ample onboard instrumentation was provided to telemeter information to the ground. This information was utilized in a ground based computer program for predicting both skin and depth doses. The shielding of the Command Module gave assurance that the skin and depth doses received would be tolerated by the crew even under the most unfavorable conditions. The doses actually received were relatively small, the largest being 1.14 rads on Apollo 14. It should be noted that the doses received on spaceflights through Apollo 15 have not exceeded doses to various organs of the body during routine X-ray diagnostic procedures (ref. 5.7).

There is a short period of time during free space (transearth, translunar, etc.) EVA when a large solar flare, should it occur, could be of medical significance. Under the worst conditions, skin doses to the crewman could be as high as 691 rad, but, because of the radiation spectrum, the depth doses still would not exceed 25 rad. Although no pathological effects are predicted as a result of such a depth dose, it is possible that the skin dose could moderately affect crew performance because of skin irritation, blepharitis, etc.

Fortunately, the probability of a large solar flare is quite small, probably no more than one in 5000 missions.

(2) Micrometeoroid Characteristics

Orbital extravehicular activity on future missions will expose the crewman's space suit to the near earth meteoroid environment for periods of several hours. To prevent micrometeoroid penetration of the space suit and subsequent decompression, protection must be provided to absorb micrometeoroid impacts. This has been accomplished with various suit fabrication materials which effectively break up the projectile and absorb the fragments.

Meteoroids are solid particles moving in interplanetary space that originate from both cometary and asteroidal sources. Because of their velocity, density, and mass, they can be hazardous to EVA crewmen. The type and extent of the potential danger depends on the protection afforded the EVA crewman and on his exposure time in space, as well as on the meteoroid characteristics. For purposes of identification, "meteoroids" are classified as sporadics, when their orbits are random, and as streams (or showers) when a number of meteoroids have nearly identical orbits. A "meteor" is a light phenomena associated with the interaction of a meteoroid with the earth's atmosphere. The portion that survives interaction with the atmosphere and is found on the surface of the earth is a "meteorite".

This section treats only the meteoroid environment of cometary origin in the mass range between 10^{-12} and 1 gram (micrometeoroids) at one

astronomical unit (1 A.U.) from the sun near the ecliptic plane. In this region (1 A.U.), the contribution of asteroidal particles to the total meteoroid population is considered to be negligible (ref. 5.31). The meteoroid descriptions and the associated density and velocity characteristics presented herein are for engineering application in the design of EVA space suit assemblies for near-earth orbit, translunar and lunar orbit, and lunar surface missions.

Meteoroid Velocities

The geocentric velocity* of meteoroids is expected to range from 11 to 72 km/sec on the basis of celestial mechanics. Analyses of photographic and radar observations of meteors entering the earth's atmosphere have confirmed this range of meteoroid velocity. Typical distributions of meteor velocities from photographic measurements display two velocity peaks. The second peak, near 60 km/sec in the distribution, is attributed to meteoroids in retrograde orbits, since their higher entry velocities are more easily detectable than the slower direct orbit meteors. This selection effect tends to give a distorted picture of the proportionate number of meteors in direct and retrograde orbits. A velocity distribution based on constant mass tends to compensate for the velocity bias inherent in the photographic technique. Average velocity values, determined from photographic measurements are : 20 km/sec by Dohnanyi (ref. 5.32); 19 km/sec by Dalton (ref. 5.33); 22 km/sec by Whipple (ref. 5.34); and 30 km/sec by Burbank, et al (ref. 5.35). On the basis of the velocity information primarily from photographic meteor measurements and the assumption of independence of mass and velocity, an average atmospheric entry velocity of 20 km/sec has been adopted as the average velocity of sporadic meteoroids. The probability-velocity distribution for this average velocity is given in Figure 5-27 (ref. 5.31).

Meteoroid Density

The density of micrometeoroids is uncertain. As in the case of meteoroid mass, micrometeoroid density is not a measured quantity. Although meteorites have been examined (90% of them being generally stoney in character with an average density of 3.5 gms/cm^3 and the remaining 10% iron-nickel with an average density of 7.8 gms/cm^3), they are generally considered to have been meteoroids of asteroidal origin. Considerations of meteoroid density to be dealt with are those related to particles which result from the break up of cometary nuclei. The cometary meteoroid has been described by Whipple (ref. 5.36) as a conglomerate of dust particles bound together by frozen gases or "ices" while Opik (ref. 5.36) postulated a dust ball. The

*Although incorrect, the term "velocity" has been used in the literature to express the speed of meteoroids.

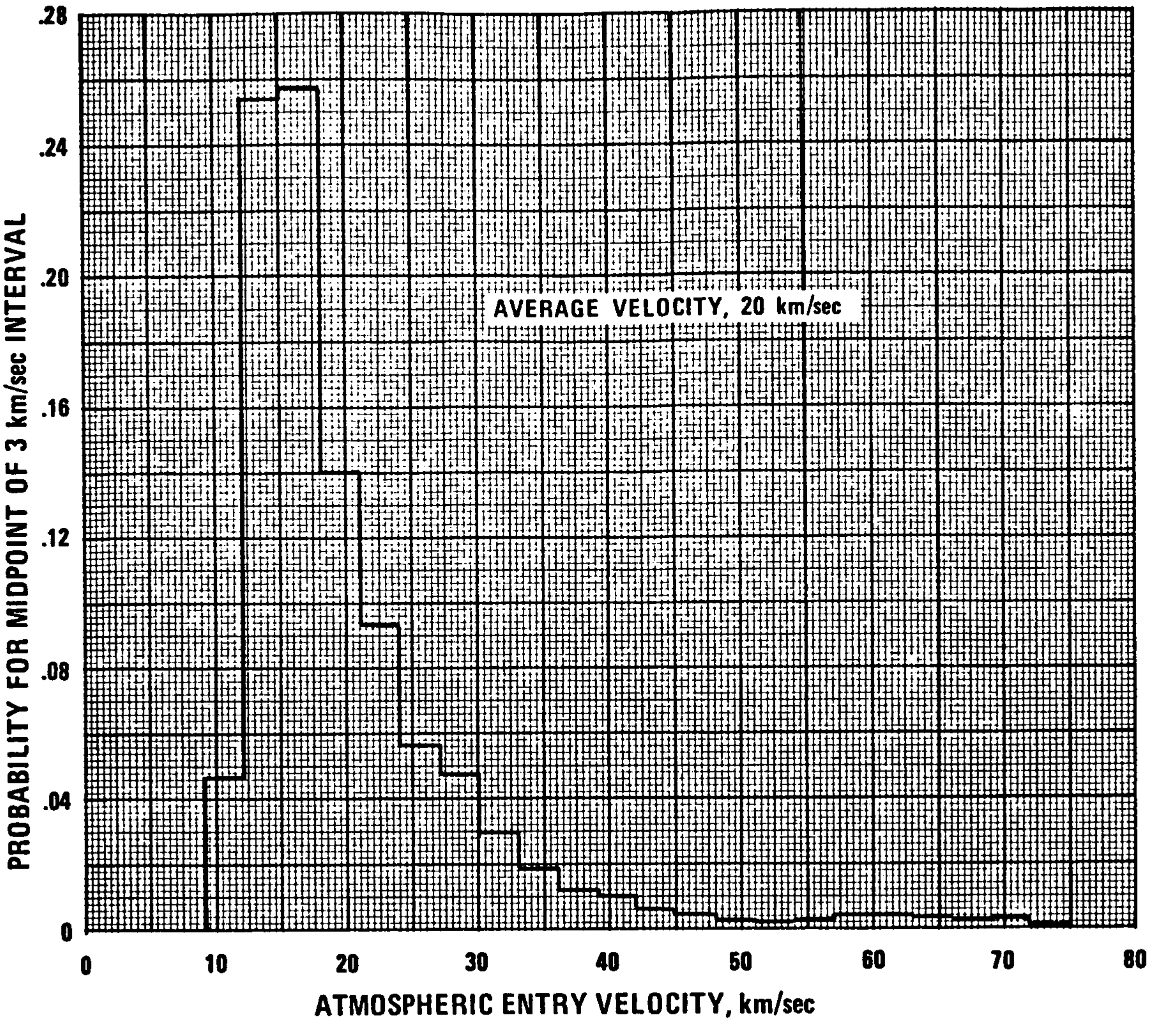


FIGURE 5-27: Probability-Velocity Distribution for Sporadic Meteoroids

flux-mass relationships, developed by each, assumed a mass density less than 1 gm/cm^3. Values of density calculated from photographic and radar observations (refs. 5.34, 5.37, 5.38, and 5.39) have ranged from 0.16 gm/cm^3 to 4 gm/cm^3. In assessing the available density data, related assumptions, and calculation procedures, Whipple's opinions that the lower densities obtained from radar-observed meteor data were not reliable and that the higher densities were not typical of cometary debris were taken into consideration. From the assessment, 0.5 gm/cm^3 has been chosen as the value for the mass density of meteoroids (sporadic and stream) of cometary orgin (ref. 5.31).

EVA Space Suit Testing

Micrometeoroid environment testing on the Gemini space suit was based on an anticipated initial extravehicular mission including

10 minutes of exposures to the external space environment. To avoid mission timing constraints, exposure was assumed to occur during the worst shower period. The meteoroid protective coverlayer design used on the Gemini suits was proof-tested with simulated meteoroids. The Gemini G4C suit configuration was qualified to provide a 0.999 probability of no penetration (P_0) of the bladder. With the system pressurized to 3.7 psig, samples of 4" x 4" swatches of the meteoroid coverlayer on the bladder were impacted with simulated meteoroids. Since these projectiles approximate the meteoroidal energy that is absorbed by the coverlayer, a corresponding P_0 for a 10-minute exposure was determined. The exposure was for a near-earth orbit and 25 ft^2 of surface area on the space suit. The composition and density of the test projectiles are listed below:

Composition	Density, gm/cc	Diameter, μ	Velocity range, km/sec	P_0
Cork and epoxy	0.53	300	24 to 27	0.99988
Pyrex glass	2.2	350	5 to 6.5	.99959
Pyrex glass	2.2	400	5 to 6.5	.99977
Boro silicate	2.4	510	5 to 6.5	.99991

A pyrex glass sphere 274 microns in diameter at a velocity of 6 km/sec approximates the energy necessary to obtain a P_0 of 9.999 for a 10-minute exposure. Based on these studies, the G4C suit was determined to be adequate for the Gemini missions.

Samples of lexan and merlon polycarbonate helmet visor material were pressurized to 3.7 psig and impacted with glass spheres accelerated to hypervelocity. The projectile impact energy was progressively increased, until the sample was perforated or a leak occurred. An examination of the targets revealed that the 0.098-inch-thick merlon and lexan withstood the impact of a 0.0156-inch glass sphere at a velocity of 6 km/sec without spalling or leakage. This projectile energy, when extrapolated to meteoroidal velocity and density, corresponded to a P_0 of 0.99993 for 135 minutes' exposure.

The space suits developed for the Apollo Program were required by NASA to survive the meteoroid environment as defined in NASA SP-8013, Meteoroid Environment Model - 1969. The criteria developed in that document are contained in Appendix F. The Integrated Thermal Meteoroid Garment (ITMG), helmet, and gloves for the Apollo and advanced space suits are required to pass the NASA micrometeoroid tests.

5.2.3.4 Weightlessness Adaptation

Prior to the United States' manned spaceflights, the space environment gravity was expected to produce certain medical and physiological effects because of its increase at the time of launch and reentry and its absence during actual flight. Although it is not the purpose of this section to fully discuss the physiological and biomedical aspects of spaceflight, it should be noted that there have been no "surprises" in the flight program to date (ref. 5.13). A summary of the medical aspects of past spaceflights are contained in Appendix D. The discussion presented in this section is concerned with the effects of weightlessness on the crewman immediately upon subjection to the zero environment.

In practically all of the United States' spaceflights, the crewmen have reported an initial feeling of fullness in the head after attaining weightless flight. The sensation has lasted for varying lengths of time ranging from a few hours to as long as three days on the Apollo 15 flight. Moderate inflight illness occurred on the Apollo 9 flight; however, it was not possible to state definitely that the effects were those of weightlessness, since obviously they could result from a complex of factors in the spaceflight situation. On Apollo 15, one crewman experienced slight giddiness which precluded rapid head or body movements. The problem disappeared shortly after landing on the lunar surface and did not recur on returning to the zero gravity environment. The Apollo 8 flight plan required that the crewmen leave their couches early in the mission in order to prepare for translunar injection. Each of the crewmen noted stomach uneasiness and awareness, and nausea was experienced on occasion by some of the crewmen during the first day of flight.

Some soreness in the costo-vertebral area has been reported. The crewmen have related this to body position while resting in the fetal position in the weightless state. There have been no serious consequences, and the condition has been relieved by hyperextension and exercise. The crewmen have generally adapted well to the weightless environment, finding it pleasant and of assistance to them in accomplishing inflight activities. They also had some interesting observations upon return to a one-gravity situation on earth. The crewmen reported a feeling that their clothing was extremely heavy, as if they had weights in the pockets. There were also sensations of being extremely heavy when placed upon the examining table postflight -- to the extent of wanting to hold onto the sides of the table (ref. 5.6, 5.7).

Spaceflight weightlessness adaptation has not presented a major problem in the performance of orbital extravehicular operation on past U.S. flights. The EVAs have been scheduled to assure that all adaptive sensations to weightlessness have disappeared prior to preparation for spacecraft egress. This philosophy should be adhered to on future missions (except contingency operations), since any symptoms would be compounded because of the increased crewman activity in preparation for and conduct of extravehicular functions.

5.2.4 Biomedical and Physiological Aspects of Past Orbital EVAs

The Gemini and Apollo safety monitoring philosophy was carried over from the Mercury project but involved two- and three-man astronaut teams, extravehicular activities and much longer flights. In addition to the safety monitoring requirements, further medical aspects of the Gemini and Apollo orbital extravehicular activities were principally concerned with the physiological responses to high space suit workloads, high thermal stresses and low fatigue tolerance. Prior to the first Gemini EVA, it was realized that work outside the vehicle would demand extreme caution. The tasks to be performed on the first EVA mission were simulated in zero-g aircraft flights, in altitude chambers, and on reduced friction devices. The EVA crewmen were monitored by one lead of electrocardiogram, respiration, and voice. The first crewman was to perform the extravehicular activity by means of slow and deliberate movements and evaluate a hand held maneuvering unit. This activity was successfully completed, but very high heart rates were recorded during EVA hatch closing activities.

There was extremely varied experience with the Gemini EVAs through mission XI, with many problems involving excessive metobolic rate production. Two Gemini EVA missions were terminated prior to completion due to overloading both the crewman and life support equipment. Although high heart rates were associated with the first U.S. (Gemini IV) EVA mission, it provided confidence to proceed with the assurance that man could accomplish EVA objectives without undue physiological constraints. Therefore, biomedical instrumentation requirements for subsequent EVA flights were reduced to one lead of ECG and one impedance pneumograph. Figure 5-28 shows the heart rate and respiration rate for the Gemini IV EVA mission.

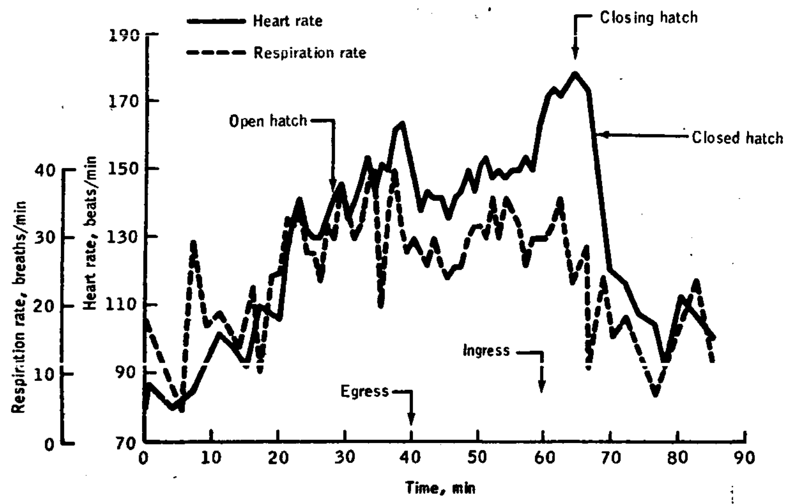


FIGURE 5-28: Physiological Characteristics for Gemini IV - Umbilical EVA (ref. 5.61)

The planned EVA for Gemini VIII was not performed due to early flight termination. One EVA crewman on Gemini IX-A was required to evaluate the operation of an Astronaut Maneuvering Unit (AMU) in the unfamiliar extravehicular environment. During this flight, greater insight into the complexity of EVA was gained. The tasks were much more difficult than anticipated. The Gemini IX-A pilot experienced considerable difficulty maintaining position. He was unable to activate the AMU and discontinued the EVA due to visor fogging. Heart rates and respiration rates throughout the various events are shown in Figure 5-29.

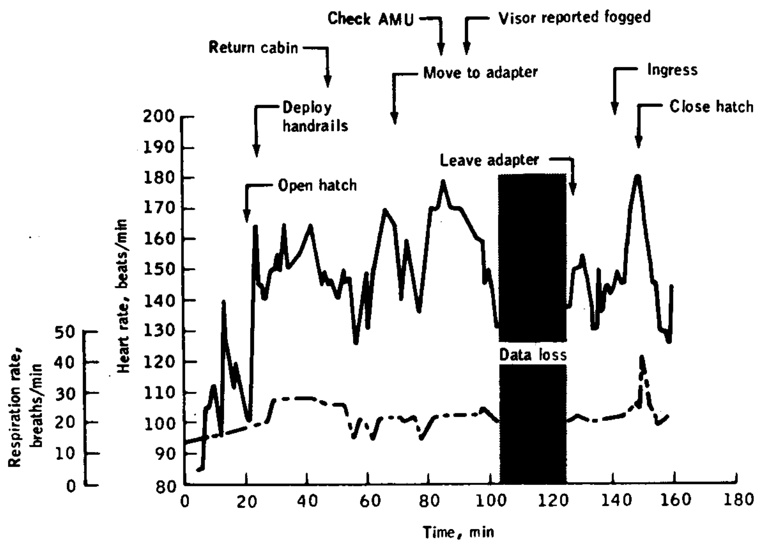


FIGURE 5-29: Physiological Characteristics for Gemini IX-A - Umbilical EVA (ref. 5.61)

The EVA during Gemini X was simplified as reflected in the physiological data shown in Figure 5-30. There was no backpack, and no strenuous complicated procedures had to be performed. The pilot was able to translate to the Gemini VIII vehicle and back to the spacecraft using a hand held maneuvering unit. (Heart rates remained at a relatively low level until hatch closure. Because there was no unusual psychogenic stimulus at this point, the increase in heart rate was attributed to the physical activity of closing the hatch.) During Gemini XI, it became apparent that excessive workloads were becoming a problem. While preparing for EVA, the pilot experienced procedural difficulties connecting his life support system and attaching his extravehicular visor, and he expended considerably more energy than was planned for EVA preparation. After egress, he experienced difficulty moving about the spacecraft and maintaining position while performing assigned tasks. At this point in the flight, there was to be a rendezvous and docking with the Agena. One of the astronaut's first tasks was to attach the Agena tether to the spacecraft at the docking bar. This was simply a fitting which slipped over the docking bar and tightened with a handle much like a water faucet. He was able to accomplish this, but not without exhausting himself to the point that it was considered unwise to

continue the planned EVA. The physiological characteristics for the Gemini XI EVA are shown in Figure 5-31.

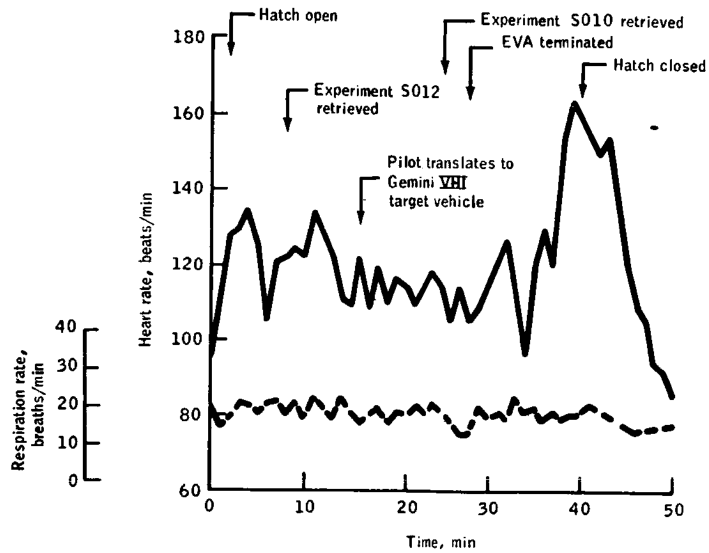


FIGURE 5-30: Physiological Characteristics for Gemini X - Umbilical EVA (refs. 5.6 and 5.55)

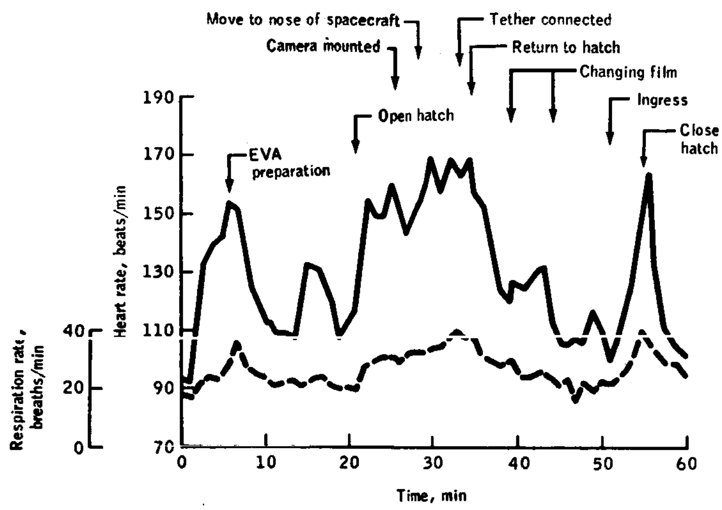


FIGURE 5- 31 : Physiological Characteristics for Gemini XI - Umbilical EVA (ref. 5.61)

With one EVA flight remaining in the Gemini Program, the problems that had developed required a reëvaluation of the extravehicular concept. Excessive workloads during EVA appeared to be a limiting factor. Evaluation of the flight data indicated that there was excessive thermal loading imposed upon the extravehicular crewman. The high respiration rates encountered during Gemini XI indicated that a buildup in the carbon dioxide level may have been a problem. Since there were no actual data on thermal conditions, oxygen, or CO_2 levels, and no direct measurement of metabolic load, the evaluation of these problem areas was compromised. In view of the problems, however, a quantitative, cumulative indication of workload which could be instantaneously available to the flight controllers during flight became a necessity. During the pre- and postflight periods of Gemini IX, X, XI, and XII, an exercise capacity test was performed by each pilot using a Collins bicycle ergometer. During these tests, the subject performed a measured amount of work increasing in 15 watt increments while heart rate, respiration rate, and blood pressure were monitored and periodic samples of expired gas were collected for analysis by the Scholander method. Time volumes of expired air, O_2 intake, and CO_2 output were also computed. The results of the pre- and postflight ergometry studies were reduced to heart rate versus oxygen utilization curves for controlling work rates during EVA missions.

After assessing previous flight and preflight data accumulated on Gemini XII, it was decided that in future EVAs the crewman would be advised of any sustained rate at or above 140 beats/min so he would be aware of his specific status and could appropriately reduce his activity. If the heart rate exceeded 160 beats/min the crewman would be advised to stop all work activities.

In planning for Gemini XII, care was taken to keep any sustained workload reduced to a level which was commensurate with the capabilities of the life support system. (The major factors which apparently produced the highest workload prior to Gemini XII were insufficient suit mobility, inadequate stabilization restraints, and human engineering factors. The effects of these factors were cumulative, as demonstrated by the pilot of Gemini XI in his effort to attach an Agena tether to a docking bar.) Design problems made this task much more difficult than had been expected. Inadequate position restraints required the crewman to expend an excessive amount of energy attempting to maintain body positioning; and, while attempting to straddle the spacecraft nose, he found that working against the space suit in order to force his legs into position was not possible. Furthermore, the resulting body position necessitated arm movement in a region which was unnatural for the inflated suit. The workload subjectively described by the pilot was confirmed by the observed heart rates and respiration rates. The Gemini XII extravehicular activity was a controlled EVA in which the tasks were carefully standardized and simulated in water immersion facilities prior to the mission. Figure 5-32 is a plot of the heart rate related to events during the Gemini XII umbilical EVA. The one peak in excess of 140 beats/min exemplified a potential danger of using heart rate as a single index of work performed. At that time, the crewman was engaged in an unscheduled, spontaneous activity. It is believed that psychogenic factors were responsible for the observed heart rate. The crewman was asked to decrease his activities, and the rate returned to an acceptable level in less than a minute.

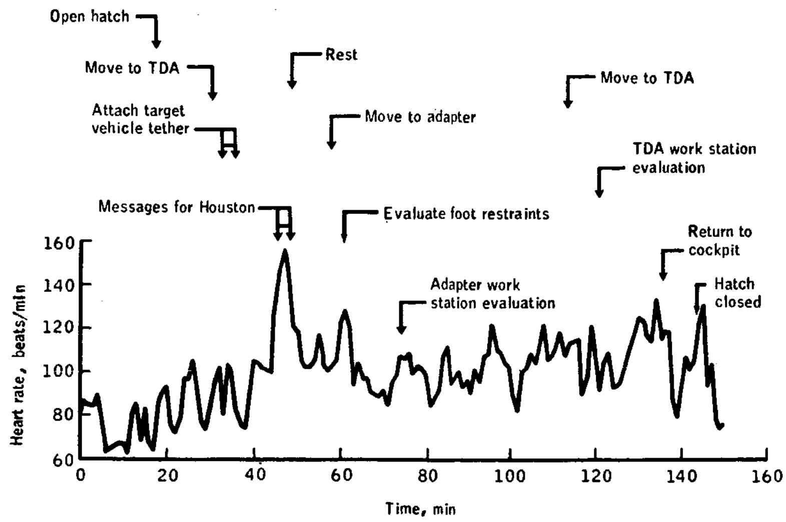


FIGURE 5-32: Physiological Characteristics for Gemini XII - Umbilical EVA (ref. 5.61)

The major biomedical conclusion derived from the Gemini EVAs was that an accurate method of estimating metabolic rate inflight is mandatory for crewman safety by allowing real-time monitoring and control of extravehicular activity. This was accomplished using three independent methods on the Apollo 9 orbital EVA and was used during all lunar surface extravehicular functions. The three methods are discussed in Section 5.2.6. Several conclusions indirectly associated with biomedical and physiological aspects that relate to future flights were also derived from the Gemini EVA experiences. These included the following:

(1) Extravehicular life support systems must be sized to provide sufficient crewman support for off-nominal situations such as those experienced on the Gemini EVA mission.

(2) Space suit mobility restrictions constituted a limiting factor in performing EVA tasks and required improvement for future EVA missions.

(3) Human engineering of foot restraints, handholds, mobility aids, translation hardware, etc. is mandatory for accomplishing satisfactory orbital EVA.

(4) Representative simulations, particularily underwater, should be used for EVA procedures development and crew training. Zero-g aircraft and ground simulations are also important.

(5) The use of flight configuration hardware is essential for effective crew training for EVA.

Each of the aspects listed above that introduced problems during the Gemini Program were greatly improved or completely corrected for later orbital EVA missions.

The Apollo 9 EVA mission, where the workload was relatively light compared to Gemini EVA, was completed without biomedical difficulty. The EVA lasted 47 minutes with the following physiological profile:

EVA Time:	47 mins
Btu Produced:	500 (600 Btu/hr average)
Heart Rate:	66-88 beats/min
Work Rate:	600 Btu/hr
*PLSS Use:	110 mins
PLSS Btu Removal:	1170 Btu

*Portable Life Support System

The metabolic rate for the Apollo 9 EVA was based on three independent evaluations: heart rate, oxygen consumption and liquid cooling garment thermodynamics (see Section 5.2.6).

No problems were encountered during the later Apollo translunar extravehicular operations. The Apollo 15 pilot commented that he experienced no difficulty in the task performance operations or translation difficulties. His heart rate was 130 beats/min until he became accustomed to the extravehicular environment, at which time it dropped to 97 beats/min.

In summary, there are three aspects of orbital EVA that require special attention and should serve as future guidelines in EVA planning. These guidelines are:

(1) The provision of sufficient inflight metabolic rate information to assure crewman safety and workload control.

(2) The provision of adequate support equipment to guarantee proper crewman restraint and translation, and

(3) The conduct of extensive preflight simulation, testing, and realistic crew training exercises to assure complete familiarization with EVA procedures and with the operation of EVA hardware.

5.2.5 EVA Biomedical and Physiological Monitoring Standards and Guidelines

5.2.5.1 Background

The inflight data telemetered to earth for medical monitoring during the Mercury, Gemini and Apollo missions are of three types: biomedical/physiological, spacecraft environmental, and operational performance. The biomedical/

physiological data for the crewmen include electrocardiographic records and data on respiration, pulse, body temperature, blood pressure, etc. The environmental data included measurements of acceleration rate, space suit and liquid cooling garment inlet and outlet temperatures, carbon dioxide partial pressure, cabin pressure, etc. The operational performance data have been restricted for the most part to what each crewman did or said; however, more elaborate monitoring is being prepared for Skylab and other future missions.

In planning the Mercury biotelemetry system, a requirement was established for continuous recording of the selected variables which would be made available immediately after telemetry acquisition to the ground based medical monitoring team. Continuous records were felt necessary to determine each crewman's capability for completing a mission and to provide clues in the event of precipitous collapse. Since survival was the main goal, the biomedical monitoring philosophy became known as "safety monitoring". Medical interest centered on the cardiovascular system because hydrostatic changes were the most obvious accompaniment of the weightless state. Instrumentation considerations consequently focused on the acquisition of cardiovascular information. Two pairs of electrodes, with two electrocardiogram (ECG) leads, were required to increase reliability. These leads, however, were located in nonstandard body areas in order to reduce body movement interference. The classical wave form was thus sacrificed in favor of improved information on cardiac rate and rhythm. Control of both venous blood pressure and arterial pressure were considered very valuable, although, at the start of the Mercury project, there was no known way to measure venous blood pressure using prudent medical practice and working within the spacecraft's operational requirements. Neither were there techniques available for the continuous measurement of arterial pressure. Blood pressure measurement was, therefore, not included at the start of the space program, although, by the time of the MA-6 Mercury flight, a semiautomatic apparatus for blood pressure measurement was used.

Body temperature was also considered an important parameter to be monitored, based on experience with near fatal hyperthermia in the Man-High balloon flights. Body temperature was monitored on all Mercury missions through MA-8 with a thermistor rectal probe. In the last Mercury flight, an oral sensor was used for pilot comfort. Finally, a measure of respiration was considered mandatory for crewman safety monitoring. Volume and rate information was preferred, but rate alone was acceptable. The first Mercury flights used a thermistor mounted on the microphone pedestal in the pilot's helmet, but it did not give reliable respiration traces and was replaced with impedance pneumograph techniques. The impedance pneumagraph reflected chest movement as well, and, from the standpoint of determining crewman survival, the detection and measurement of chest movement was of more value than were indications of air flow.

In addition to the above information, cabin environmental data (pressure, temperature, etc.) and voice communication with the astronaut were provided to the medical monitoring team. The physiological variables measured for Project Mercury were the minimum considered vital to ensure pilot safety and give planners confidence in extending flight time. No measurements were taken solely to investigate man's reaction to spaceflight (ref. 5.40).

It should be emphasized that evaluation of the astronaut's physiological response utilized several information sources in addition to the telemetered physiological data. These sources included control baseline data, voice responses in flight, answers to debriefing questions, and detailed postflight physical examination. Postflight detection of orthostatic hypotension (a radical drop in blood pressure and rise in heart rate following upright tilt) in the last two Mercury missions provided the primary indication of a potentially serious medical problem. It caused some apprehension concerning the 14-day exposure planned in the upcoming two-man Gemini flights and was a significant medical finding of the Mercury Program.

The Mercury safety monitoring philosophy was carried over to the Gemini Program, which involved much longer flights. The same four parameters, electrocardiogram (two leads), respiration, body temperature, and blood pressure, were measured on both command pilot and pilot. The most significant difference was the improvement in packaging and system design, and the addition of an onboard biomedical recorder. On Mercury, only the biomedical sensors were located within the pressure suit. From the sensors, wires passed out through a connector to signal conditioners packaged on plug-in, printed circuit boards. With Gemini, the signal conditioners were miniaturized and mounted in pockets on the crewman's undergarment. The new arrangement minimized lead length from the sensors (improving the signal quality) and the signal conditioners were completely redesigned to provide higher input impedance, higher common mode rejection, lower output impedance, higher accuracy, and greater stability. Although no gross medical problems were encountered in the Mercury flights, NASA was concerned that circulatory deconditioning might prove a limiting factor to the longer (8-day) weightless exposure that would be required for the planned lunar missions by reducing the astronaut's ability to withstand reentry acceleration stress. This concern led to a revision in the planned Gemini flight schedule, resulting in an increase in flight duration (flights were approximately doubled to 14 days) to qualify man for the admittedly shorter, but more arduous lunar missions. It also led to a change from pure safety monitoring equipment to inclusion of medical experiments designed to reveal more subtle body changes.

It is significant from the hardware requirement standpoint that only two of the Gemini experiments utilized bioinstrumentation in addition to the safety instrumentation. These were the phonocardiogram experiment and the electroencephalogram (EEG) experiment. Thus, the safety instrumentation was able to serve multiple functions in the spaceflight program.

The Apollo safety bioinstrumentation requirements were relaxed somewhat from the previous requirement for continuous and comprehensive monitoring, since the previous flights had revealed fewer hazards and deleterious effects than had been anticipated.

The Apollo Program increased the flight team size to three with its main objective a lunar landing and return. Approximately the same measurements were made on Apollo as on Mercury and Gemini, but at less frequent intervals, and for only one of the three astronauts at a time. Exceptions were during the extravehicular activity and Lunar Excursion Module (LEM) mission phases. At

these critical times, medical safety information transmission is continuous, although fewer variables are measured. The change in Apollo information requirements was made because the successful 14-day Gemini flight was considered adequate qualification of man for the shorter lunar missions (ref. 5.40). The biomedical parameters monitored on the Mercury, Gemini and Apollo flights are shown in Table 5-10 (ref. 5.41).

TABLE 5-10: Types of Biomedical Monitoring from Spacecraft

Factor Monitored	Mercury (1-man Crew)	Gemini (2-man Crew)	Apollo (3-man Crew)
ECG	Bipolar electrodes	A&S[a], 320[b]	A&S[a], 200 sps[b]
Respiration	Thermistor and impedance pneumograph	Impedance method, 40 sps; axillary ECG electrode used as sensor	Impedance-pneumograph, 40 sps
Blood Pressure	Arm cuff and microphone	Manual, squeeze-bulb, brachialocclusive system	Mechanical, squeeze-bulb, ad libitum
Body Temp.	Rectal probe and oral sensor	Oral thermistor probe; 1.2 sps; intermittent	Oral, mechanical, ad libitum
PKG[c]	None	Routed with EEG to tape recorder (experiments data)	200 sps

[a]Axial and sternal. [c]Phonocardiographic.
[b]Samples per second.

Because of the high metabolic heat production during the Gemini orbital EVA missions, methods were needed to accurately obtain metabolic data for the design of lunar portable life support systems and to keep the crewman's work rate within safe limits. Three methods were developed and are currently in use: (1) the heartrate based upon preflight ergometric data, (2) oxygen consumption based on portable life support system oxygen bottle decay, and (3) the liquid cooling garment inlet-outlet heat balance. These metabolic rate "evaluators" will be discussed in Section 5.5.2.7.

The biomedical monitoring during Skylab EVA will include respiration, heart activity, and body temperature. These parameters will be monitored through the individual crewman operational bioinstrumentation systems (see Section 3.8.2). During the EVA missions, two crewmen will egress the Airlock

Module to perform solar astronomy data retrieval tasks. A third crewman will be space-suited in the Multiple Docking Adapter but will not be pressurized. EVA biomedical data will be recorded in the Orbital Workshop and played back to the Manned Space Flight Network immediately following EVA completion. In addition to these biomedical measurements, the Skylab biomedical experiments program offers the first step in the United States' space program for collecting detailed data on man and his adjustment to the space environment.

5.2.5.2 EVA Biomedical Monitoring Standards and Guidelines

To date, NASA has not developed a precise set of EVA biomedical monitoring standards or requirements for earth orbital spaceflights. The monitoring requirements for past flights were based somewhat on the availability of specialized bioinstrumentation, the shortage of space and weight allocations on the spacecraft, and the cost of space qualified instrumentation; monitoring requirements were based primarily on monitoring crewman health and safety. Since the crewman's biomedical responses and aptitudes in the weightless space environment are more easily studied inside the spacecraft, the EVA monitoring requirements on future missions will still be primarily concerned with crewman safety.

The parameters monitored (including biomedical, physiological and environmental parameters) during EVA operations have been based on the safety and experimental requirements of each specific space mission. From the single lead used to measure heart rate, respiration and voice during Gemini EVA, ten (10) measurements will be monitored and displayed on the flight surgeon's ground based medical console during the manned Skylab Program (ref. 5.42). The parameters monitored for each EVA crewman on Skylab are presented in Table 5-11 and are recommended, not as a standard, but as a guide to planning future EVA missions. Additional information concerning medical monitoring requirements can be found in NASA Manned Spacecraft Center document No. MSC-03987, Medical Research and Operations Directorate, Skylab Medical Data Requirements.

5.2.6 EVA Bioinstrumentation Hardware

The bioinstrumentation hardware that is worn by or attached to the crewman during orbital extravehicular operations is of particular interest. The electrocardiogram (wave patterns, rate), the impedance pneumograph, and the body temperature measurements require direct sensor contact with the crewman, while the signal conditioners and supporting hardware are worn usually as a belt or harness. A number of important problems affecting the quality of the bioelectrical information received from the electrodes and the reaction of the crewman's skin to the electrodes must be considered during extended spaceflight. The electrode attachment substance (conducting medium) is also important to signal quality. Should electrode problems develop, electrical noise can reduce or destroy the usefulness of the signals received, or discomfort and danger of infection may require removal or relocation of the electrode before mission completion. More important, discomfort can interfere with the crewman's ability to perform assigned tasks during critical periods.

The ECG and respiration electrodes normally consist of metal plates contacting the skin through a layer of conductive paste. The most important

TABLE 5-11: EVA Biomedical and Safety Monitoring Parameters

PARAMETERS MONITORED	SAMPLING RATE (Samples Per Second - SPS)
Crewman Identification	1.25
Biomedical	
Body Temperature	1.25
Heart Rate	10.00
Impedance Pneumograph	80.00
ECG Wave Form	160.00
Environmental	
Suit Oxygen In	1.25
Suit Oxygen Out	1.25
Liquid Cooling Garment Temperature In	1.25
Liquid Cooling Garment Temperature Out	1.25
Space Suit Total Pressure	1.25

requirements of the electrodes for long-term monitoring in space are: (1) secure mechanical attachment, (2) reliable electrical contact, and (3) the capacity of the conducting medium to remain moist. There are also certain criteria from the electrical, mechanical and medical aspects that the electrodes and their attachment to the skin must meet. These criteria are important in affecting signal quality, and they include:

- No electrode polarization; the electrode must exhibit a total reversibility of measured potential with a reversal of current.
- Low contact resistance between the metallic electrode unit and the living skin surface.
- No spurious signals generated within the electrode assembly during vibration, mechanical contact of space suit, etc.
- No damage to the site of electrode application (skin) during the recording period.
- No noticeable discomfort while wearing the electrode assembly.

- No cumulative toxic effects caused by repeated electrode application, and no delayed effects caused by long-term contact.

These conditions are difficult to meet during recording periods of extended duration in the space environment, particularly while the crewman is in his space suit. Because of this difficulty, NASA concentrated on the development of electrode systems and conducted extensive tests on human subjects, focusing the attention of these studies on skin-to-electrode resistance. The results produced a basic fluid-filled electrode that has been used for all United States manned spaceflights, with the exception of Apollo 16, which used a new sponge-type electrode. A discussion of skin electrodes is presented, since temporary signal losses have occured on U.S. spaceflights.

The principle of the fluid-filled electrode is isolation of the electrode from the skin by use of a conductive paste to provide the skin-to-electrode electrical path. This configuration reduces spurious signals caused by relative movement between the electrode and the interfacing electrolyte. The fluid electrode developed for Mercury, Figure 5-33, consisted of a ring of molded RTV silicone rubber that supported a disc of 40-mesh, stainless steel screen. A coaxial cable passed through the side of the ring, with the central conductor soldered to the screen. After application, the electrode formed an open cavity sealed to the skin with an adhesive. Supported in the center of this cavity was the stainless steel screen which electrically contacted the skin via an electrolyte filling the cavity. After the addition of the electrolyte, the end of the cavity was covered with a moisture-proof tape. These electrodes gave less background noise than the standard clinical metal plates. There was also less baseline shift when the region of attachment was actively moved.

During the Mercury flights, the monitored ECG signal was susceptible to movement artifact, probably due to polarization of the stainless steel mesh electrode. Also, the soldered junction of the copper lead to the mesh screen caused spurious signals and unwanted noise because of electrolytic action of the dissimilar materials. Modifications were made to the Mercury electrode design to circumvent these problems for the Gemini flights (ref. 5.40). The electrode developed for Gemini was fabricated from a pure silver disc (Figure 5-34). Holes drilled in the disc permitted mobility of the electrolyte. The electrode lead was soldered to the disc; however, the soldered junction in this case was insulated with an epoxy coating. The disc was anodized in a solution of sodium chloride to produce a thin coating of silver chloride. The RTV silicone rubber electrode housing supported the silver disc in a circular groove which maintained the disc above the skin. Electrodes fabricated in this manner were found to reduce the noise effects experienced in the Mercury flights. This improvement can be attributed to the silver-silver chloride disc which provides an electrochemically reversible (nonpolarizing) electrode. The epoxy-protected solder junction reduced spurious signals (ref. 5.40).

The electrodes used on most of the Apollo flights included the use of a rigid plastic cup to house the silver-silver chloride electrodes and the elimination of all soldering. Construction details of the Apollo electrode are shown in Figure 5-35. Each electrode consists of a Plexiglas type VS 647-10 housing, a silver electrode disc, a wire lead, and a connector. The silver

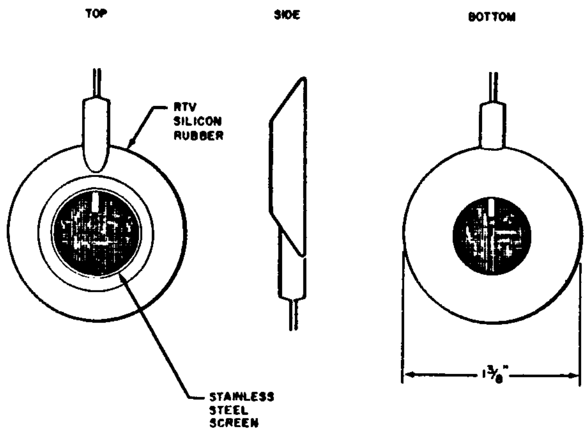


FIGURE 5-33: Project Mercury ECG Electrode

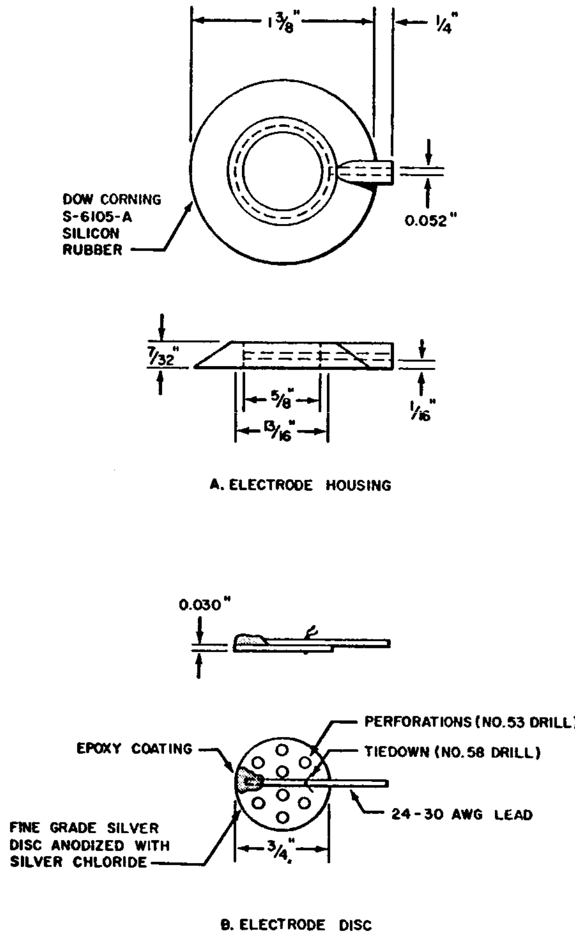


FIGURE 5-34: Gemini ECG Electrode

disc is coated with a thin deposit of silver chloride, applied by the technique developed for the Gemini electrodes. The lead consists of a length of clear, 26-gauge, Teflon-coated copper wire percussively welded to the electrode silver disc and the electrode connector. This welding process completely precludes lead contamination. After the lead is attached to the silver disc, the disc is sealed to an inner shoulder of the electrode housing, and the top cavity is filled with epoxy. This encapsulates the backside of the disc, the wire junction, and a short length of the lead wire. Minor modification of the electrode wiring and quick disconnect pin connectors were incorporated following the Apollo 7 flight, since the sternal electrocardiograms of two crewmen were lost, one during lift-off and one in flight. Replacement and relocation of the electrodes was required during several of the Apollo flights. This was due to excessive "noise" and drying of the electrode paste. Operation was returned to normal after replacement. Several electrode pastes were developed and tested by NASA to preclude objectionable irritation during prolonged use. These have been generally acceptable with some minor skin irritation and a few cases of crewmen being allergic to certain paste solutions. The composition of the

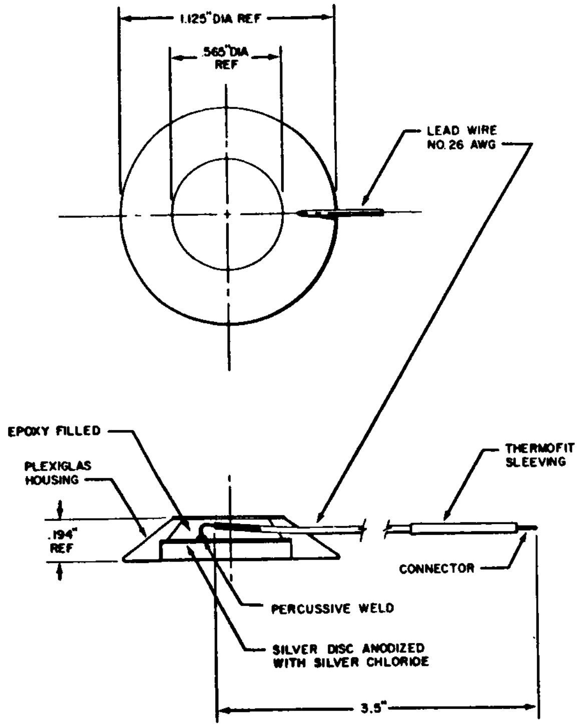


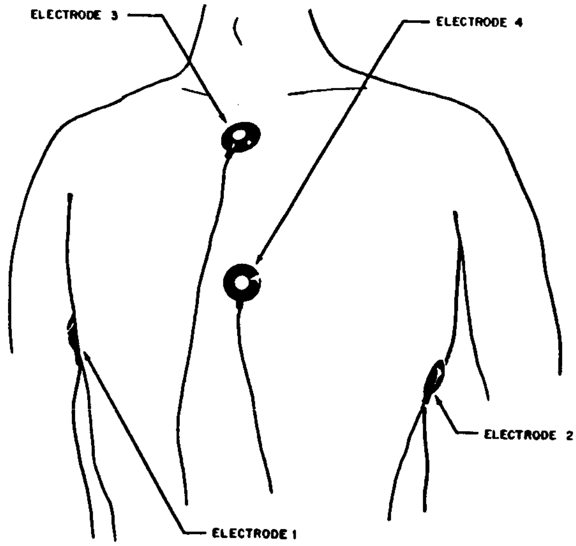
FIGURE 5-35: Apollo ECG Electrodes

various pastes can be obtained from the NASA Medical Research and Operations Directorate (MR & OD), Manned Spacecraft Center, Houston, Texas. Numerous methods and solutions used in the application of electrodes have been developed by NASA with varying degrees of success. This information can also be obtained from NASA MR & OD. Due to past problems of electrode application, an inflight electrode application kit was available on the Apollo flights and is scheduled for use on Skylab. The choice of the anatomical sites for electrode placement was made by NASA after extensive investigations of the ease, convenience, validity, and reliability of signal sensing for various lead configurations. The original Mercury ECG electrode scheme included three electrodes for two ECG leads, with one electrode common to both measurements. However, to make both measurements completely independent, the three-electrode system was changed to four. The electrode sites are illustrated in Figure 5-36, they were the bilateral mid-axillary line (electrodes 1 and 2) and the anterior midline of the episternal area (electrodes 3 and 4). The axillary lead consisted of one electrode placed at the base of the rib cage on the right side with the left electrode placed on the rib cage at the third intercostal space. The sternum lead was roughly at right angles to the axillary lead, with one electrode placed on the manubrium and the other at the xiphoid process. The choice of these sites was based on the following:

- The sternum has very little underlying muscle tissue and thus reduces the possibility of electromyographic artifact effects.

- The intercostal (rib) muscles also generate very small electromyographic potentials, even under conditions of rather violent activity.

FIGURE 5-36: Anatomical Placement of ECG Electrodes



- The data from these two lead configurations correlate very well with traditional data from standard ECG leads.

The axillary lead was found to be additionally useful when, in later flights, the impedance pneumograph was used for extracting respiration data. The impedance pneumograph requires one set of electrodes across the thorax at the mid-axillary line, and at the sixth or seventh intercostal space. Development of compatible electronics allowed the impedance pneumograph and ECG amplifier to share the same set of electrodes (ref. 5.40).

The Mercury Program used two types of body temperature sensors -- a rectal probe, incorporating a thermistor sensing unit, and an oral sensor. A skin temperature probe, consisting of a thermistor in a thermoinsulated disc, was also developed but was not used on Mercury. The Mercury rectal probe and skin sensor are shown in Figure 5-37. For the Gemini flights, an oral temperature sensor (Figure 5-38) was substituted for the rectal probe. The sensor consisted of a finger-formable Teflon-covered thermistor assembly attached to a small section of machined polycarbonate. The polycarbonate section contained a Velcro pad for easy attachment inside the crewman's helmet. Used with appropriate signal conditioning equipment, the oral temperature probe covers the range of 95° to 105°F with an accuracy of 0.05 percent.

A skin temperature sensor (Figure 5-39) was developed for the simulation chamber bioinstrumentation system used in the Apollo Program. This sensor consists of a thermistor mounted at the center of a plastic support which serves to hold the thermistor against the skin with moderate pressure, to provide good protection for the thermistor, and to ensure ventilation and accurate skin temperature sensing. Temperature measurement range is 80° to 115°F ± 0.3° using compatible electronics. The sensor, however, was not used during the

Apollo flights. Oral and mechanical equipment was favored, instead, for its ease of operation and accuracy (ref. 5.40).

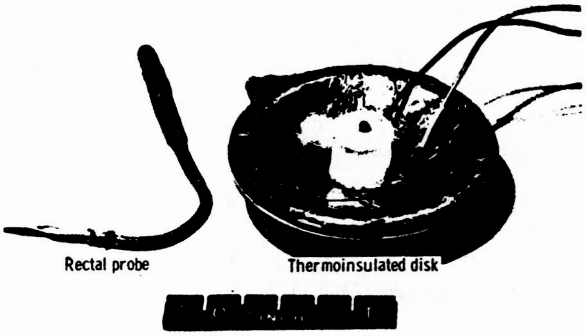


FIGURE 5-37: Mercury Body Temperature Sensors

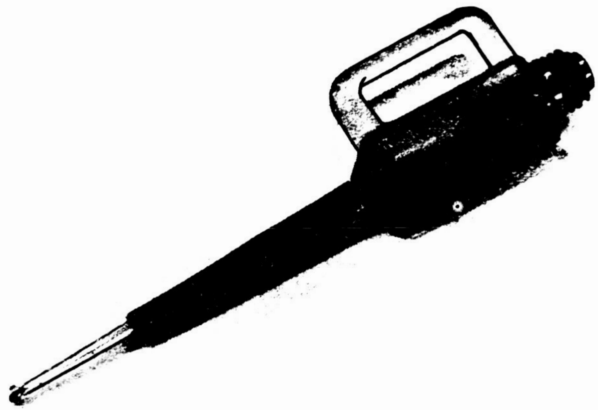


FIGURE 5-38: Oral Temperature Sensor Used in the Gemini Flights

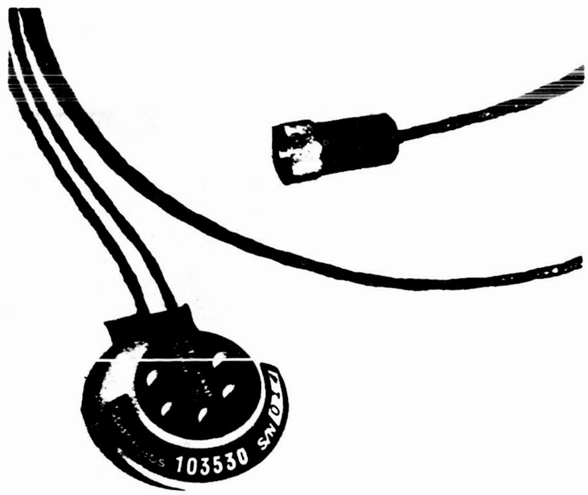


FIGURE 5-39: Skin Temperature Sensor -- Apollo Simulations Only

The biomedical signal conditioners, usually worn in a specially designed compartmented belt, are important because this system largely determines the form of the biomedical information supplied to the system monitor, and it directly influences his concept and interpretation of the crewman's physiological status. In a bioinstrumentation system, the signal conditioner operates between the primary sensor (electrode) and the processing and display units. The basic signal conditioner consists only of amplifiers and filters. In other cases, a signal conditioner may include some computational elements, or serve as a telemetry transmitter. Most of the NASA spaceflight signal conditioners are primarily the basic type which prepare the biological signal for telemetry (or on-board recording) and ground processing. Since many NASA publications have given detailed descriptions of the Mercury, Gemini and Apollo signal conditioners and their bioinstrumentation systems, that information will not be repeated here. However, a pictorial description of the hardware directly in contact with the space-suited crewman is warranted.

The bioinstrumentation system used on the Gemini flights is shown in Figure 5-40; Figure 5-41 depicts the Gemini bioinstrumentation belt and sensors fitted to a subject. The Apollo bioinstrumentation system components worn by the crewmen are shown in Figure 5-42 (ref. 5.41).

The development and qualification of new instrumentation for biomedical monitoring, due to its highly specialized design, fabrication and qualification processes must begin well before a particular space mission and must be controlled closely up to the time it is used. Most of the major planning elements and decision processes required to provide NASA bioinstrumentation are shown in the flow chart in Figure 5-43 (ref. 5.40).

5.2.7 Metabolic Monitoring

The metabolic cost of task performance experienced during the Gemini EVA missions caused concern in planning lunar surface and future orbital extravehicular functions. At least two of the Gemini EVA missions were terminated short of completion due to overloading both the crewman and his life support equipment.

There were no metabolic measurements taken during the Gemini flights. Instead, metabolic cost calibrations were determined by use of bicycle ergometry prior to flight. Heart rate was correlated to metabolic heat production at various work rates for each crewman and calibration curves developed for inflight heart rate comparison.

Two metabolic cost measurement methods, in addition to heart rate comparisons, were developed and used for real-time metabolic monitoring during Apollo 9 EVA and during the lunar surface activities. Oxygen usage from the space suit life support system was measured as a second estimation. The liquid cooling garment (LCG) inlet and outlet temperatures were recorded for calculating the third metabolic rate estimation. Each of these inflight metabolic rate estimators are briefly discussed on the following pages.

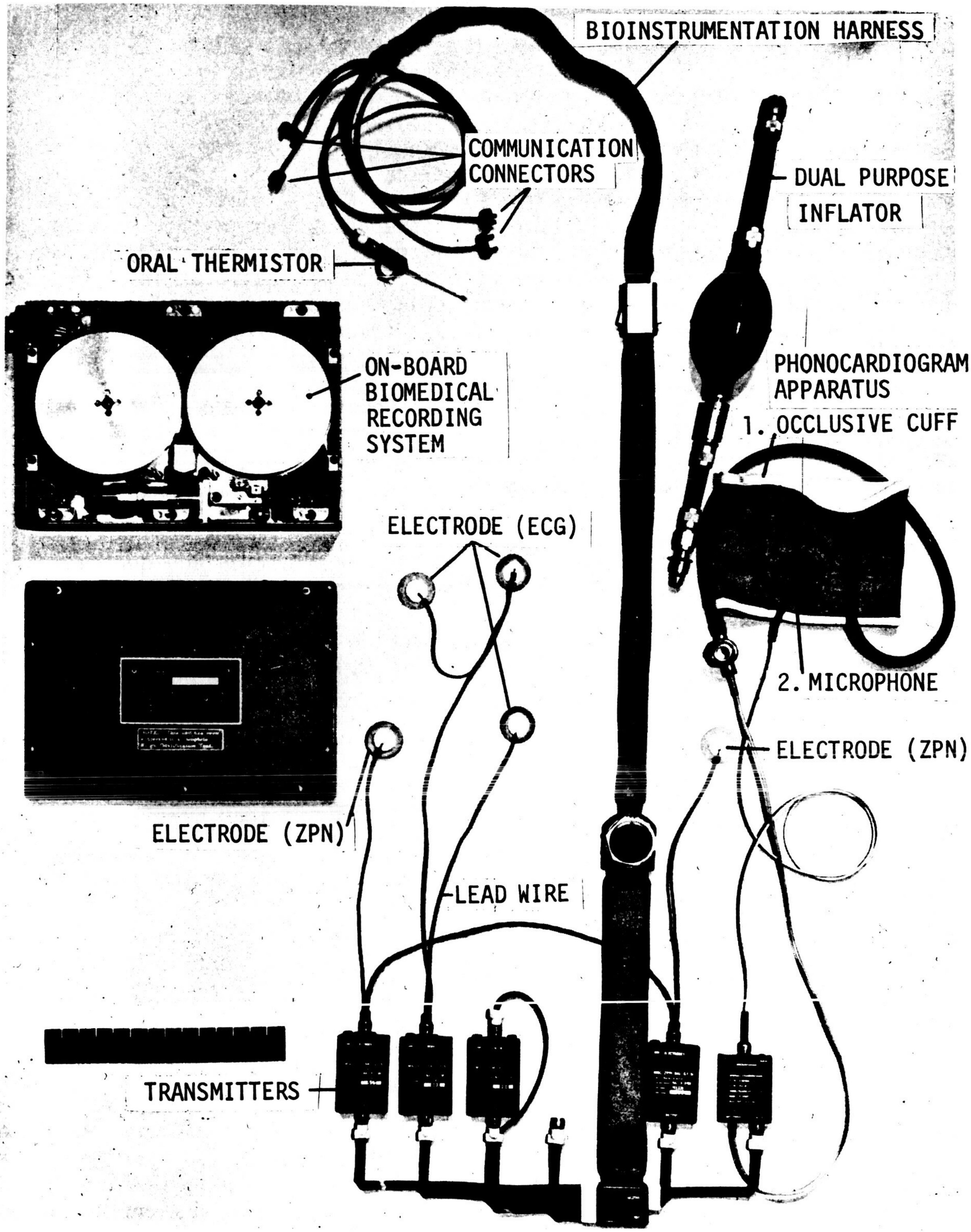


FIGURE 5-40: Bioinstrumentation System Used on Gemini

FIGURE 5-41: Fitted Bioinstrumentation System for Gemini

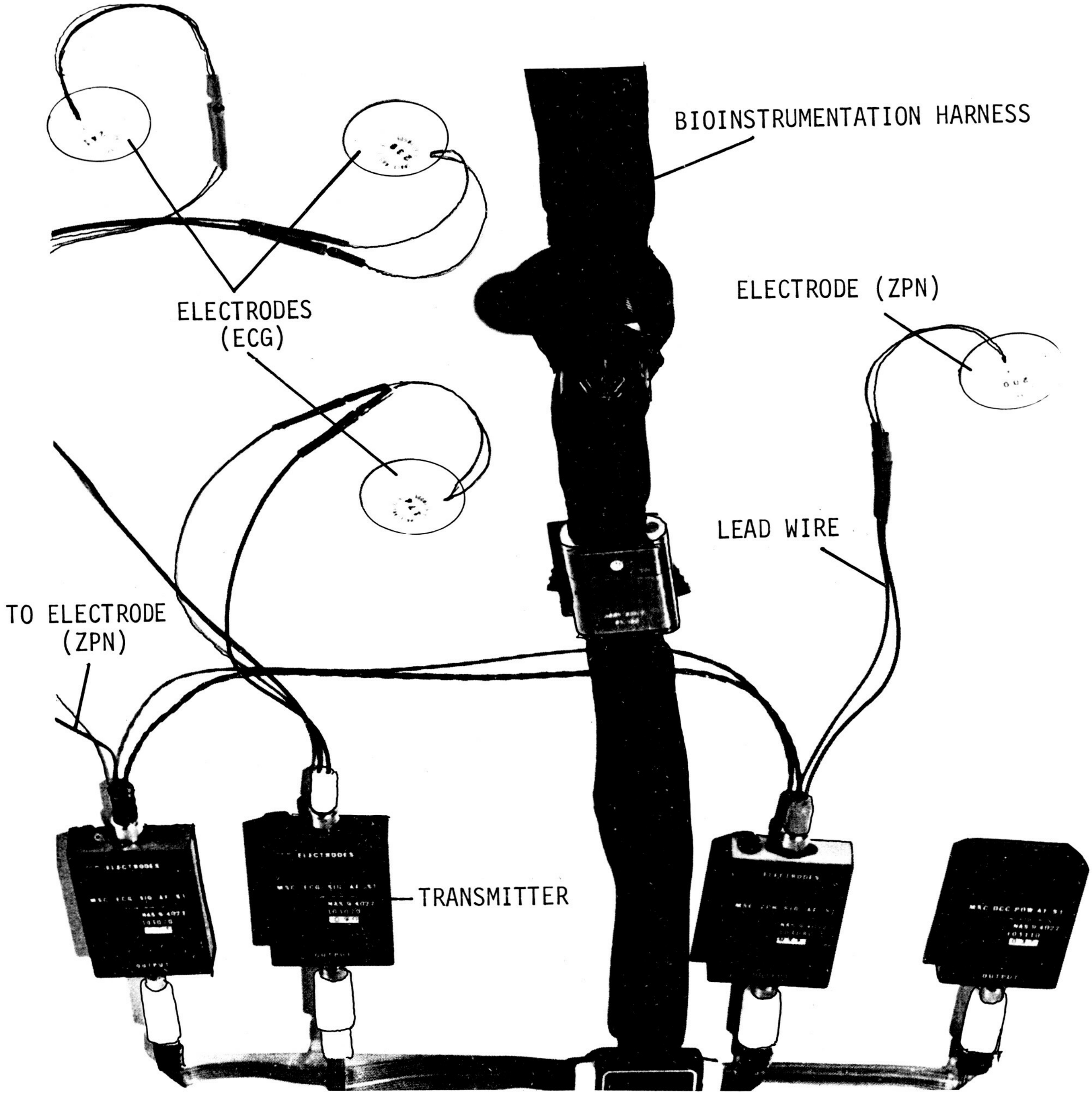


FIGURE 5-42: Bioinstrumentation System Used on Apollo

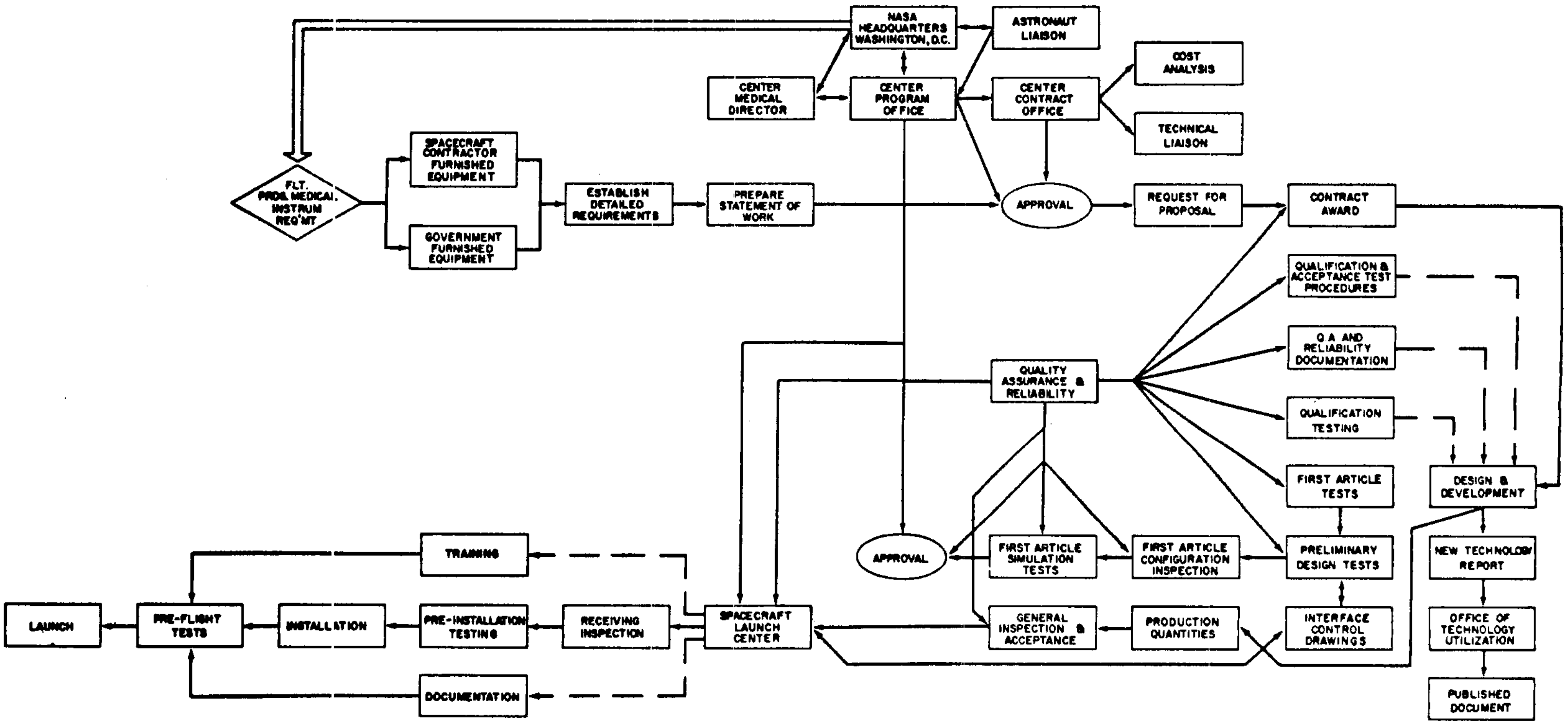


FIGURE 5-43: NASA Procedures for Development of Bioinstrumentation

5.2.7.1 Heart Rate Method

The effective use of this method is contingent upon the accurate measurement of the crewman's heart rate. The raw ECG wave form is subject to significant alteration by potential muscle action interference and by sensor movement. These artifacts have a frequency content greater than 20 Hz. The information content of the QRS complex of each ECG wave form (one beat) is primarily in a band from 15 to 20 Hz. Taking advantage of the frequency differences between the noise and information, a high Q selection amplifier is used which allows for optimum discrimination of the cardiac QRS complex. This amplifier is also cascaded with a second-order low pass filter. The 3-decible point of the filter is set to 20 Hz, and it provides a significant rejection of muscle artifact and noise.

The output of the amplifier/filter is detected at a certain level by a monostable multivibrator. The multivibrator produces an output pulse of 5 volts with a 30-millisecond duration. This pulse is then sampled by the computer at a rate of 50 per second. After the ECG pulse is detected by the computer, additional software filtering is employed through an automatic blanking loop which inhibits the counting of unwanted ECG event pulses for a variable duration. The duration of the blanking control is inversely related to heart rate. The computer is then effectively used as an event counter which registers the number of times the ECG pulse is set to the "on" condition within a period of 15 seconds. This count is multiplied by four and the result is displayed on a numeric cathode ray tube. A 1-minute heart rate is obtained by averaging four successive values from the 15-second counts. By means of a "sliding" interrogation, the 1-minute heart rate is updated every 15 seconds.

The heart rate to metabolic rate conversion is contingent on the relationship between metabolic expenditure and heart rate. The linear regression curve is constructed from laboratory data when the crewman is calibrated. The calibration procedure is as follows: The crewman is instrumented for the ECG. He is seated on a bicycle ergometer and breathes into a mouthpiece which is attached to sample container bags (Douglas bags). With the crewman in a rested state, a known volume of expired respiratory gases is collected. The crewman then proceeds with the exercise portion of the calibration and is brought to the desired heart rate by varying the workload via a closed loop work-to-heart-rate computer. When a steady state is reached at a desired value, the expired respiratory gas samples are collected. The method is repeated at heart rates of 110, 120, 130, 140, and 150 beats per minute. Oxygen uptake and CO_2 production are calculated from the gas samples and are used to calculate a metabolic rate corresponding to the specific heart rate. A linear regression curve relating heart rate and metabolic rate is constructed from the derived data sets (ref. 5.43). The method used for heart rate to metabolic rate real-time computation is contained in Appendix G.

5.2.7.2 Oxygen Consumption Method

This method is based on the relationship between the rate of oxygen consumption and metabolic rate. The estimation of the crewman's metabolic rate by this method is based on standard laboratory techniques with the exception

that carbon dioxide production is not monitored. The calculations of metabolic rate and total energy expended are based upon the life support system oxygen bottle pressure decay. Since no instrumentation is available for monitoring the volume of CO_2 produced, the respiratory quotient (RQ) is empirically estimated from the experience obtained during thermal vacuum crew training. A negative oxygen leakage rate at the start of an EVA, equivalent to the assumed metabolic rate until the life support system oxygen bottle pressure decay, is established. At this time the oxygen leakage rate is adjusted to a positive value corresponding to the value obtained in suit pressure integrity checks. This is to adjust for the fact that, during the initial part of the EVA, there is no oxygen bottle pressure decay because of the suit to ambient pressure differential of 3.85 psid (ref. 5.43). Methods used for determining the oxygen consumption metabolic rate estimates are shown in Appendix G.

5.2.7.3 Liquid Cooling Garment Method

The liquid cooling garment (LCG) method is based on the heat production of the crewman and on the thermodynamic changes in the EVA life support system. The metabolic rate is predicted from telemetry data on the water inlet temperature and the change in temperature in the LCG. Computer calculations are altered by changing the program inputs for the heat exchange between the inside and the outside of the suit or by changing the "factor instruction" (Fac) in the program to different levels of sensitivity. The program makes an initial estimate of the metabolic rate, based on an empirical linear relationship between heat removal by the LCG and the total metabolic rate. Then the inlet temperature is used in combination with the heat-balanced equations to estimate the sweat rate, and the final estimate of metabolic rate is determined by using an empirical input command (ref. 5.43). The monitoring procedures used in estimating the LCG metabolic rate are also included in Appendix G.

During the Apollo 9 EVA, the Lunar Module pilot's heart rate ranged from 66 to 88 beats/min, with an average of 75 beats/min. His metabolic rate was determined by the three methods described above. The correlation using the three estimators is shown in Table 5-12.

TABLE 5-12: Apollo 9 EVA Metabolic Rate Data (Lunar Module Pilot)

Method	Total Btu Produced
Heart rate	520
Liquid Cooling Garment Thermodynamics	523
Oxygen Bottle Pressure Decay	497

The work rate during the extravehicular activity was about 600 Btu/hr. A total of 1170 Btu were removed by the portable life support system during the 110-minute period of use. Compared to the extravehicular activity during the Gemini Program, this workload was exceedingly light. (Studies on earth

have demonstrated that healthy subjects can walk in a pressurized suit at rates above 2000 Btu/hr without rest for periods in excess of an hour. Much higher, e.g., in excess of 3000 Btu/hr, rates can be sustained for 10 minutes or more.) The three methods are used for real-time metabolic monitoring during lunar surface EVA. Accumulated data obtained by these methods and an integrated estimate of the energy cost for the Apollo 11 Commander (CDR) and Lunar Module pilot (LMP) during EVA are summarized in Figure 5-44 and 5-45. These data showed that the oxygen usage and LCG methods gave energy cost levels 61% below those estimated by the heart rate method in the CDR and 81% above those estimated by the heart rate method in the LMP. The oxygen usage and LCG methods not only yielded similar data, but also reflected well the physical activity observed by television monitoring. The loss in accuracy of the heart rate method might be attributed to many causes, including psychological, heat storage, and cardiovascular deconditioning effects on the heart rate, and poor correlation of slow heart rates with energy cost. The integrated energy costs during extravehicular activity of the Apollo 11 LMP on the lunar surface is further detailed in terms of Btu production while performing specific tasks in Table 5-13. The highest heart rates recorded were from 140 to 160 beats per minute in the CDR during lunar sample collection and transfer of the sample box to the LM.

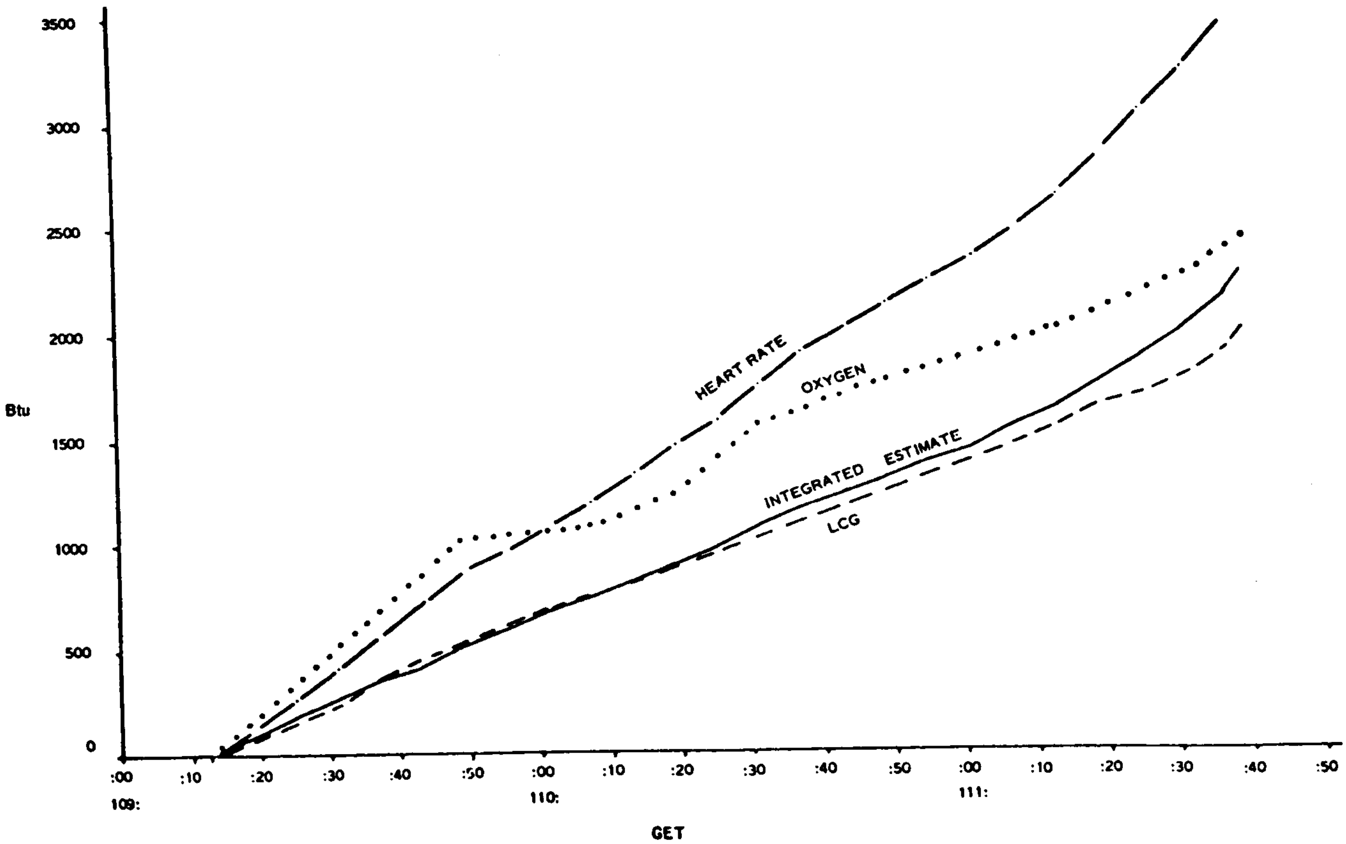


FIGURE 5-44: Accumulated Data on Energy Cost of the Apollo 11 Commander during Extravehicular Lunar Surface Activity

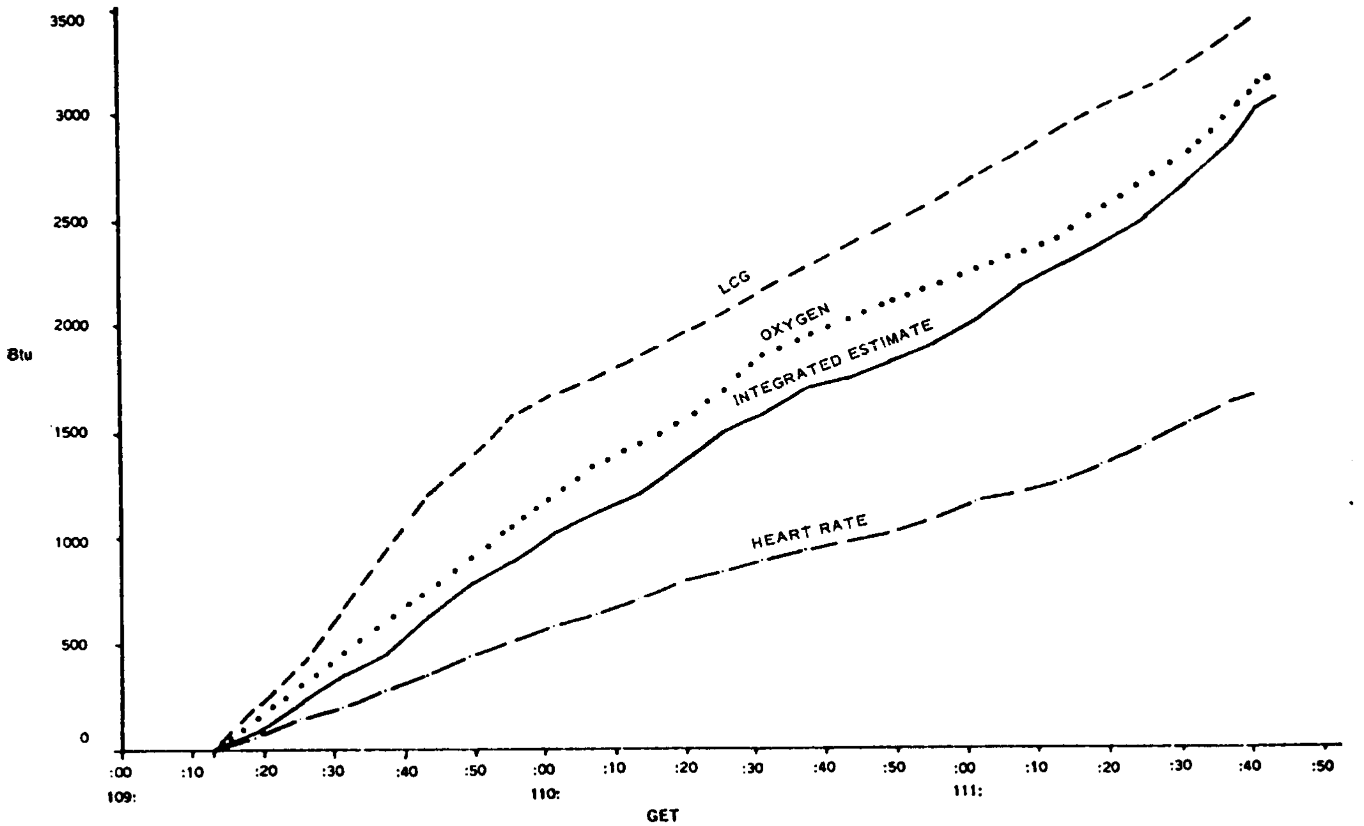


FIGURE 5-45: Accumulated Data on Energy Cost of the Apollo 11 Lunar Module Pilot During Extravehicular Lunar Surface Activity

To summarize, it has been found that even though the energy cost of performing a given task differs among crewmen, the average hourly total energy cost for the crewmen during lunar surface activity is 900 to 1200 Btu/hr. Sufficient data are not available for average energy costs during orbital EVA; however, Gemini and Apollo data indicate that orbital EVA for periods of 5 to 6 hours is not outside man's physiological limits. The LCG method appears best for estimating energy cost of work for use in consumable calculations. On the other hand, the heart rate method is a valuable relative indicator, but it is a poor absolute indication of the energy cost of work (ref. 5.7).

TABLE 5-13: Integrated Lunar Surface Energy Cost of the Apollo 11 Lunar Command Pilot During EVA

Events	Time		Integrated BTU Production		
EVA—Lunar Surface	G.E.T.* (Hours:Minutes)	Interval (Minutes)	Rate (BTU/Hr)	Total BTU For Interval	BTU Accumulated
Assist and Monitor CDR	109:13	26	1200	500	
Initial EVA	109:39	5	1950	163	683
Environmental Familiarization (Television Cable Deployment)	109:44	14	1200	280	963
Solar Wind Composition Deployment	109:58	6	1275	128	1091
Flag and Presidential Message	110:04	14	1350	315	2270
Evaluation EVA Capability (Environment)	110:18	16	850	227	1633
Lunar Module Inspection	110:34	19	875	277	1910
EASEP Deployment	110:53	18	1200	360	2270
"Documentary" Sample Collection (Solar Wind Composition Recovery)	111:11	12	1450	290	2560
EVA Termination (Ingress) (Sample Return Container)	111:23	14	1650	385	2945
Assist and Monitor CDR	111:37	2	1100	37	2982
Close Feedwater	111:39				
TOTAL		146			2982

*Ground elapsed time.

REFERENCES

5.1 Manned Spacecraft Center: Preliminary Design Requirements for Shuttle EVA/IVA Orbiter Support, NASA/MSC Internal Note MSC-EC-R-71-10, Houston, Tex., September 30, 1971.

5.2 Manned Spacecraft Center: Summary of Gemini EVA, R. M. Machell (ed.), NASA SP-149, Houston, Tex., 1967.

5.3 Matrix Man Systems: Skylab EVA Task Analysis, Huntsville, Ala., August 1971.

5.4 "Worden Takes First Deep Space Walk", Aviation Week and Space Technology, August 9, 1971.

5.5 Manned Spacecraft Center: Gemini Summary Conference, NASA SP-138, Houston, Tex., February 1-2, 1967.

5.6 Berry, Charles A. "Medical Experiences in Manned Space Flight", Aerospace Medicine, Vol. 32, 1971.

5.7 Berry, Charles A. "Summary of Medical Experience in the Apollo 7 through 11 Manned Spaceflight", Aerospace Medicine, Vol. 41, No. 5, May 1970.

5.8 Lovelace Foundation for Medical Education and Research: Compendium of Human Responses to the Aerospace Environment, NASA CR-1205 (III), Vol. III, Section 12, 1968.

5.9 Kapstens, A. I. and B. E. Welch. "Spacecraft Atmospheres", Aerospace Medicine, Vol. 30, Second Edition, 1971.

5.10 Samonski, F. H. and E. M. Tucker. Apollo Experience Report - Command and Service Module Environmental Control System, NASA TN-D-6718, March 1972.

5.11 Lovelace Foundation for Medical Education and Research: Compendium of Human Responses to the Aerospace Environment, NASA CR-1205 (III), Vol. III, Section 10, 1968.

5.12 Fletcher, J. G. "Energy Costs", Bioastronautics Data Book, P. Webb (ed.), NASA SP-3006, 1964.

5.13 Hessberg, R. R. "Space Medicine - Present and Future", XXth International Congress of Military Medicine and Pharmacy, Brussels, Belgium, July 1971.

5.14 Mitchel, E. L. "Carbon Dioxide Build-Up Characteristics in Spacesuits", Aerospace Medicine, August, 1969.

5.15 Lovelace Foundation for Medical Education and Research: Compendium of Human Responses to the Aerospace Environment, NASA CR-1205 (III), Vol. III, Section 6, 1968.

5.16 Howard, D. C. and R. G. Syversen. "Selection of Astronaut Cooling Systems for Extravehicular Space Missions", AIAA 4th Thermophysics Conference, June 1969.

5.17 Wortz, E. C., D. K. Edwards, R. A. Diaz, III, et al. "Study of Heat Balance in Full Pressure Suits", Aerospace Medicine, Vol. 38, 1967.

5.18 NASA: Bioastronautics Data Book, SP-3006, P. Webb (ed.), Washington, D.C., 1964.

5.19 Blockley, W. V., J. W. McCutchan and C. L. Taylor. Prediction of Human Tolerance for Heat in Aircraft: A Design Guide, WADC-TR-53-346, May 1964.

5.20 Thomas, A. A. "Toxicology of Aerospace Systems", Aerospace Medicine, Vol. 13, Second Edition, 1971.

5.21 Berry, Charles A. Preliminary Clinical Report of the Medical Aspects of Apollos 7 and 8, NASA TMX-58027, May 1969.

5.22 Allen, T. H. and S. E. Beard. "Decompression Sickness in Simulated 'Zoom' Flights", Applied Physiology, Vol. 26, 1969.

5.23 Wilson, C. L. "Emergency Pressurization of Aerospace Crews", Aerospace Medicine, Vol. 17, Second Edition, 1971.

5.24 Clamann, H. G. "Decompression Sickness", Aerospace Medicine, Vol. 7, Second Edition, 1971.

5.25 Clemedson, C. J. "Space Ionizing Radiation as a Problem in Space Missions", XIXth International Astronautical Congress, Stockholm, Sweden, 1968.

5.26 Lovelace Foundation for Medical Education and Research: Compendium of Human Responses to the Aerospace Environment, NASA-CR-1205 (III), Vol. III, Section 3, 1968.

5.27 Saksonov, P. P., V. V. Antipov, and B. I. Davydov. Problems of Space Biology, "Nauka" Press, Moscow, 1968 (NASA TT F-604, Vol. 9, February 1972).

5.28 Pickering, J. E. "Radiobiological Concepts for Manned Space Missions", Aerospace Medicine, Vol. 41, No. 2, February 1970.

5.29 Serendipity Associates: A Description Model for Determining Optimal Human Performance in Systems, NASA TR 296634, October 1966.

5.30 Busby, D. E. A Prospective Look at Medical Problems from Hazards of Space Operations, Lovelace Foundation for Medical Education and Research, NASA CR-856, Albuquerque, N. Mex., July 1967.

5.31 NASA: Meteoroid Environment Model (Near Earth to Lunar Surface), NASA SP-8013, March 1969.

5.32 Dohnanyi, J. S. Model Distribution of Photographic Meteors, Bellcomm, Inc., Report TR-66-34-1, 1966.

5.33 Dalton, C. C. Statistical Analysis of Photographic Meteor Data, Part II: Verniani's Luminous Efficiency and Supplemented Whipple Weighting, NASA TMX-53360, November 1965.

5.34 Whipple, F. L. "On Meteoroids and Penetration", Journal of Geophysical Research, Vol. 68, No. 17, 1963.

5.35 Burbank, P. B., B. G. Cour-Palais, and W. E. McAllum. A Meteoroid Environment for Near-Earth, Cislunar and Near-Lunar Operations, NASA TN D-2747, April 1965.

5.36 Whipple, F. L. "The Meteoritic Risk to Space Vehicles", Vistas in Astronautics, Pergammon Press, Los Angeles, 1958.

5.37 Verniani, F. "On the Luminous Efficiency of Meteors", Research in Space Sciences, Smithsonian Astrophysical Observatory Special Report No. 145, 1964.

5.38 Verniani, F. II Nuovo Cimento, Vol. 33, No. 4, August 1964.

5.39 Ceplecha, Z. "Classification of Meteor Orbits", Proceedings of a Symposium on Meteor Orbits and Dust, NASA SP-135, 1967.

5.40 Weltman, G., et. al. NASA Contributions to Bioinstrumentation, NASA SP-5054, Spacelabs, Inc., 1968.

5.41 Jones, R. L. and E. C. Moseley. "Automated Medical-Monitoring Aids for Support of Operational Flight", NASA SP-5078, Biomedical Research and Computer Application in Manned Space Flight, 1971.

5.42 Manned Spacecraft Center: Medical Research and Operations Directorate, Skylab Medical Data Requirements, MSC-03987, Houston, Tex., July 1971.

5.43 NASA: Standard Operating Procedures for the Metabolic Assessment Team, Revision B, February 1972.

BIBLIOGRAPHIES

BIBLIOGRAPHY TABLE OF CONTENTS

BIBLIOGRAPHY OF ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS

BIBLIOGRAPHY

ENVIRONMENTAL CONTROL AND

LIFE SUPPORT SYSTEMS

1. Abramov, I. P. "Some Results of Operations of the Self-Contained Life Support System During Flight of the 'Soyuz 4' and 'Soyuz 5' Spaceships", Space Biology and Medicine, Vol. 4, No. 4, October 26, 1970, pp. 108-112.

2. Adams, D. M., L. M. Hunt, and A. E. Wudell. Integrated Maneuvering and Life Support System Simulation, Final Report, NASA-CR-99656, Martin Co., Denver, Colo., April 1969.

3. Ames Research Center: Portable Life Support Systems, Conference Papers, April 30 - May 2, 1969, NASA-SP-234, Moffett Field, Calif., 1970.

4. Annis, J. F., S. J. Troutman, and P. Webb. Automatic Control of Water Cooling in Space Suits, NASA-CR-1085, NASW-1529, Webb Associates, Yellow Springs, Ohio, June 1968.

5. Annis, J. F., S. J. Troutman, and P. Webb. "Automatic Cooling in Water Cooled Space Suits", NASW-1306, NASW-1529, NAS1-2682, Aerospace Medicine, Vol. 41, March 1970, pp. 269-277.

6. Annis, J. F., and P. Webb. "Controlled Cooling During High Rates of Work", Aerospace Medical Association 1967 Annual Scientific Meeting, April 10-13, 1967, Preprint.

7. Annis, J. F., and P. Webb. The Principle of the Space Activity Suit, NASA-CR-973, NAS1-6872, Webb Associates, Yellow Springs, Ohio, December 1967.

8. Archibald, E. R. "A Review of Some Recent and Current Exploratory Development Efforts in Pressure Suit Technology", N68-24882, AGARD Behavioral Problems in Aerospace Medicine, October 1967.

9. Barthlome, D. E. Space Suit Pressure Stabilizer, U. S. Patent #3,534,407, NASA-CASE-XLA-05332, Langley Research Center, Langley Station, Va., 1970.

10. Beggs, J. C. "Design and Development of the Apollo Extravehicular Mobility Unit", New York Academy of Sciences, Annals, Vol. 134, November 22, 1965, pp. 441-451.

11. Bell, L. E. "Operational Considerations for Extravehicular Activity as Applied to Future Space Missions", Biotechnology, 1971, pp. 255-274.

12. Bell, L. E., R. L. Frost, and J. W. Thompson. "Environmental Control System", N66-29633, Gemini Midprogram Conference, Manned Spacecraft Center, Houston, Tex., 1966, pp. 71-77.

13. Bell, L. E., R. M. Machell, J. W. Prim, and N. P. Shyken. "Summary of Gemini Extravehicular Activity", N68-14951, Gemini Summary Conference, Manned Spacecraft Center, Houston, Tex., July 1967, pp. 127-146.

14. Bentilla, E. W., C. Cafaro, A. P. Shlosinger, and W. Woo. Technology Study of Passive Control of Humidity in Space Suits, NASA-CR-69098, NSL-65-87-3, Northrop Corp., Hawthorne, Calif., September 1965.

15. Bitterly, J. G. ECGS Liquid-Phase-Change Garment Cooling System, NAS9-7207, McDonnell Douglas Astronautics Co., Santa Monica, Calif., 1970.

16. Bitterly, J. G. Evaporative Cooling Garment System (ECGS), Part 1, Final Report, NASA-CR-92332, MDAC-62364, NAS9-7207, McDonnell Douglas Co., Huntington Beach, Calif., September 1968.

17. Bixler, H. J., A. S. Hoffman, and L. A. Spano. "New Polymer Material Holds Key to Pervaporative Space Suit Cooling", Space/Aeronautics, Vol. 48, pp. 107, 108, 110, 113.

18. Bottomley, T. A., and E. M. Roth. "Thermal Environment", N69-12440, Compendium of Human Responses to the Aerospace Environment, Lovelace Foundation for Medical Education and Research, Albuquerque, N. Mex., November 1968.

19. Breeding, R. E., and R. Lang. "On Agreement Between Predicted and Actual Energy Cost Incurred During the Operation of a Space Suit System", Life in Spacecraft, 16th International Astronautical Congress, Vol. 7, Athens, Greece, September 13-18, 1965, pp. 317-337.

20. Brown, J. T., and D. A. Myers. Portable Heat Rejection Systems for the Extravehicular Astronaut, NAS9-8184, Martin Marietta Corp., Denver, Colo., 1970.

21. Burns, F. T., M. W. Horton, H. J. McMann, and E. M. Tucker. "Life Support Systems for Extravehicular Activity", N68-14947, Gemini Summary Conference, Manned Spacecraft Center, Houston, Tex., 1967

22. Burriss, W. L. Study of the Thermal Processes for Man-in-Space, NASA-CR-216, NASW-1015, AiResearch Mfg. Co., Los Angeles, Calif., April 1965.

23. Cafaro, C., J. A. Peterson, A. P. Shlosinger, and K. F. Sterrett. Analytical Review of Passive Mass Transfer of Water Vapor in a Space Suit, NASA-CR-63144, Northrop Space Labs, Hawthorne, Calif., May 1965.

24. Callin, G. D., and W. C. Kaufman. "Physiological Basis for a Passive Extravehicular Thermal Control System", Aerospace Medicine, Vol. 37, November 1966, pp. 1143-1147.

25. Chambers, A. B. "Controlling Thermal Comfort in the EVA Space Suit", ASHRAE Journal, Vol. 12, March 1970, pp. 33-38.

26. Chato, J. C., and B. A. Hertig. Regulation of Thermal Sweating in EVA Space Suits, NASA-CR-104071, NGR-14-005-103, Illinois University, Urbana, Ill., July 14, 1969.

27. Christensen, K. K. Study of Umbilical Lines for Extravehicular Operation, Part 1, Final Report, IIT Research Institute, Chicago, Ill., February 18 - May 18, 1963.

28. Christensen, K. K. Study of Umbilical Lines for Extravehicular Operation, Part 2, Final Report, IIT Research Institute, Chicago, Ill., July 22 - August 31, 1963.

29. Clodfelter, R. G., and R. A. Stewart. "The Requirements and Role of EVA Associated with Orbital Structures", Expandable and Modular Structures Conference, May 1967, pp. 345-363.

30. Copeland, R. J., F. H. Goodnight, and E. G. Lipnicky. Space Environment Simulator Test Program, Vol. 2, Unmanned Thermal Performance Evaluation of a Gemini Extravehicular Space Suit, Test Report, NASA-CR-6536, May 1965.

31. Copeland, R. J., F. H. Goodnight, and B. G. Lipnicky. Unmanned Thermal Performance Evaulation of a Gemini Extravehicular Space Suit, Vol. 1, Test Report Gemini Bravo Test Series Space Environment Simulator Test, NASA-CR-65935, NAS9-3414, LTV Aerospace Corp., Dallas, Tex., July 15, 1965.

32. Copeland, R. J., F. H. Goodnight, and R. O. Pearson. Thermal Performance Test of the A-2H Apollo Extravehicular Mobility Unit, Vol. I, NASA-CR-65280, NAS9-3414, Ling-Temco-Vought, Inc., Dallas, Tex., March 15, 1965.

33. Correale, J. V., and W. W. Guy. "Space Suits, Part II", Space World, Vol. A-2, November - December 1963, pp. 32-35.

34. Crocker, J. F., D. C. Jennings, and P. Webb. "Metabolic Heat Balances in Working Men Wearing Liquid-Cooled Sealed Clothing", AIAA and NASA Third Manned Space Flight Meeting, Houston, Tex., November 4-6, 1964, pp. 111-117.

35. Curtis, D. L. "Contingency Transfer Systems", Aerospace Medicine, Vol. 41, August 1970, pp. 946-947.

36. Curtis, D. L. "Litton Portable Life Support System", NASA Ames Research Center Portable Life Support Systems, N70-28501, 1970, pp. 127-137.

37. Curtis, D. L. "Open-Loop Portable Life Support System Lightens Crew Load", Space/Aeronautics, Vol. 52, December 1969, pp. 68, 69, 71.

38. Donahue, J. W. "Experiment D-12, Astronaut Maneuvering Unit", N67-16027, NASA, Washington Manned Space-Flight Expt., Gemini IX Mission, November 1, 1966.

39. Drake, R. M., Jr., J. E. Funk, and J. B. Moegling. "Sensible Heat Transfer in the Gemini and Apollo Space Suits", Thermal Problems in Biotechnology, American Society of Mechanical Engineers, Winter Annual Meeting, New York, N. Y., December 3, 1968, pp. 96-112.

40. Dresser, R. J., and R. N. Prince. Evaluation of Lithium Peroxide for Oxygen Supply and Carbon Dioxide Control, AIAA Paper 69-620, Fourth Thermophysics Conference, San Francisco, Calif., June 16-18, 1969.

41. Edwards, D. K., III, T. J. Harrington, and E. C. Wortz. "Metabolic Rates in Pressurized Pressure Suits", Aerospace Medicine, Vol. 36, September 1965, pp. 825-830.

42. Freedman, G. M. "Control of Man's Thermal Environment During an Extravehicular Mission", AIAA and NASA Third Manned Space Flight Meeting, Houston, Tex., November 4-6, 1964, pp. 126-131.

43. Fried, E., and G. Hieser, Measurement of Thermal Conductance of Multilayer and Other Insulation Materials, Final Report, NASA-CR-92329, General Electric Co., Philadelphia, Pa., August 5, 1968.

44. Fried, E., G. Hieser, R. B. Hobbs, and G. S. Karp. Measurement of Thermal Conductance of Multilayer and Other Insulation Materials, Final Report, NASA-CR-65797, NAS9-3685, General Electric Co., Philadelphia, Pa., September 29, 1967.

45. Garrett Corp.: Extravehicular Activity, MS-AP-1222-1, N68-85447, Los Angeles, Calif., 1966.

46. Genin, A. M., and L. G. Golonkin. "Problems of the Prolonged Autonomous Existence of Humans in Spacesuits", Life in Spacecraft, Vol. 5, 17th International Astronautical Congress, Madrid, Spain, October 9-15, 1966, pp. 159-164.

47. Goodnight, F. H. Thermal Tests of a Prototype Gemini Extravehicular System, N66-31644, Ling-Temco-Vought, Inc., Dallas, Tex., August 6, 1964.

48. Goodnight, F. H., and T. E. Mouritsen. Unmanned Extravehicular Environments Operation Qualification Test of the Gemini ELSSL Extravehicular Life Support System Test Plan, NASA-CR-65279, NAS9-3414, Ling-Temco-Vought, Inc., Dallas, Tex., September 10, 1965.

49. Gorodinsky, S. M. "Dynamics of Elimination of Some Metabolic Products by Subjects Wearing Insulated Suits", Space Biology and Medicine, Vol. 2, No. 4, November 22, 1968, pp. 125-131.

50. Gorodinsky, S. M. "Formulation of Physiological Principles for Rational Heat Transfer in Individual Insulating Gear", Space Biology and Medicine, Vol. 5, No. 3, August 12, 1971, pp. 54-62.

51. Gran, A. A., and R. Lang. Venting Device for Pressurized Space Suit Helmet, ASA-CASE-XMS-09652-1, APPL-SN-618969, Hamilton Standard, Windsor Locks, Conn., 1969.

52. Grigoryeu, Yu., and Ye. Ye. Kovalev. Radiation Safety--Space Radiation and Shielding for Spacecraft and Extravehicular Space Suits, FTD-TT-65-1682/1&4, AD-629422, Air Force Systems Command, Wright-Patterson AFB, Ohio, February 1, 1966.

53. Grossman, F. A.,and D. A. Myers. Comparative Study of Heat Rejection Systems for Portable Life Support Equipment, Final Report, NASA-CR-99619, Martin Co., Baltimore, Md., April 1969.

54. Hays, E. L., and R. S. Johnston. The Development and Operation of Extravehicular Equipment, Seventh International Astronautical Congress, Madrid, Spain, October 9-15, 1966.

55. Hedge, J. C. Survey of Thermal Control Techniques for Extravehicular Space Suits, Final Report, March 1, 1966 - March 1, 1968, AD-687149, IIT Research Institute, Chicago, Ill., December 1968.

56. Heimlich, P. F.,and T. W. Herrala. Integrated Maneuvering and Life Support System, AMRL-TR-69-41, Hamilton Standard, Windsor Locks, Conn., 1970.

57. Heimlich, P. F., T. W. Herrala, and D. C. Howard. "Integrated Maneuvering and Life Support System Containing Protective Suit, Life Support System, and Maneuvering Unit for Increased EVA Capability", NASA Ames Research Center Portable Life Support Systems, N70-28501, pp. 11-27.

58. Heimlich, P. F., J. G. Sutton, and E. H. Tepper. Advanced Extravehicular Protective System Interim Report, Hamilton Standard, Windsor Locks, Conn., July 1, 1970 - May 31, 1971.

59. Hodge, W. H. Mission D Extravehicular Activity, NASW-417, NASA-CR-96176, Bellcomm, Inc., Washington, D. C., July 1, 1968.

60. Hough, W. W. Review of EVA/IVA Life Support Equipment for AAP-ML Action Item 478, NASW-417, NASA-CR-100268, Bellcomm, Inc., Washington, D. C., December 12, 1968.

61. Howard, D. C. Engineering Design Study of a Space Suit with an Integrated Environmental Control System, Final Report, AMRL-TR-68-122, Hamilton Standard, Windsor Locks, Conn., October 1968.

62. Howard, D. C. Integrated Maneuvering Life Support System, Final Report ASA-TM-X-66902, United Aircraft Corp., Windsor Locks, Conn., May 31, 1968 - October 31, 1969.

63. Howard, Douglas C. Integrated Maneuvering Life Support System, Contract No. F33615-67-C-1946, Hamilton Standard, Windsor Locks, Conn., July 1970.

64. Howard, D. C., and R. G. Syversen. "Selection of Astronaut Cooling Systems for Extravehicular Space Missions", Journal of Spacecraft and Rockets, Vol. 7, April 1970, pp. 498-501.

65. Iles, T. L., W. J. Oreilly, and R. N. Prince. "Development of the Portable Environmental Control System", AiResearch Mfg. Co., Los Angeles, Calif., 1970.

66. Irbe, P., and J. A. Lieske. "Environmental and Mobility Constraints on the Configuration of a Nonanthropomorphic Space Suit", N68-18729, National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

67. Irbe, P., and J. A. Lieske. Study of Extravehicular Protection and Operations, NASA-CR-773, NASA Order R-21-009-00, Johns Hopkins University, Baltimore, Md., June 1967.

68. Jennings, D. C. "Water-Cooled Space Suit", Journal of Spacecraft and Rockets, Vol. 3, August 1966, pp. 1251-1256.

69. Johnston, R. S. "The Development of Space Suit Systems", IAF Second International Symposium on Basic Environmental Problems of Man in Space, Paris, France, June 14-18, 1965.

70. Kerslake, D. M. "Heat Loss in Space", First International Symposium on Basic Environmental Problems of Man in Space, Paris, France, October 29 - November 2, 1962, Hilding Bjurstedt (ed.), New York: Springer-Verlag, 1965, pp. 153-159.

71. Kincaid, W. C. "Apollo Portable Life-Support System--Development Status", ASME Aviation and Space Conference, Paper No. 65-AV-45, Los Angeles, Calif., March 14-18, 1965.

72. Knezek, R. A., and G. B. Whisenhunt. "Thermal Protection System for Extravehicular Space Suits", Technology of Lunar Exploration, Clifford I. Cummings and Harold R. Lawrence (eds.), New York, N.Y.: Academic Press, Inc., 1963, p. 433-447.

73. Kosmo, J. J., and E. M. Tucker. Extravehicular Tunnel Suit System, U.S. Patent #3,537,668, U.S. Patent APPL-SN-857445, NASA Spacecraft Center, Houston, Tex., November 3, 1970.

74. Krasnoger, L. J., B. E. Welch, and R. R. Wempen. "Physiology of Man During Steady State Exercise in a 180 mm. Total Pressure Environment", Aerospace Medical Association 1967 Annual Scientific Meeting, Preprint, Washington, D.C., April 10-13, 1967.

75. Krasnoger, L. J., B. E. Welch, and R. R. Wempen. "Physiology of Man During Steady-State Exercise in a 180 mm. Hg Environment--Hematologic, Cardiovascular and Clinical Observations, and Respiratory Function and Metabolism", Aerospace Medicine, Vol. 39, pp. 587-596.

76. Lang, R., and R. G. Syversen. "Factors Affecting the Thermal Equilibrium of a Subject in the Apollo Extravehicular Mobility Unit", New Dimensions in Space Technology, Second Space Congress, Cocoa Beach, Fla., April 5-7, 1965, pp. 269-280.

77. Lechtman, M. D., and Nachum, R. "Microbiological Evaluation of a Typical Suit Loop Heat Exchanger During Manned Testing", Aerospace Medicine, Vol. 39, pp. 988-993.

78. Lewis, B. M. "Earthman in Space", Grumman Horizons, Vol. 4, No. 2, 1964, pp. 26-28.

79. Machell, R. M. Summary of Gemini Extravehicular Activity, NASA-SP-149, NASA Manned Spacecraft Center, Houston, Tex., 1967.

80. Manned Spacecraft Center: MSC Apollo 13 Investigation Team, Panel 5C--Corrective Action Study and Implementation for Government Furnished Equipment, Final Report, NASA-TM-X-66930, Houston, Tex., 1970.

81. Maples, H. E., R. E. Sanders, and J. P. Vincent. Engineering and Operational Experiences Related to Lunar-Surface, Thermal-Vacuum Qualification of the Apollo Extravehicular Mobility Unit, AIAA Paper 69-992, AA/NASA, Manned Spacecraft Center, Houston, Tex., September 1969.

82. Martin, R. J. "Transient Thermal Study of a Space Suit Clad Astronaut on the Moon", The Challenge of Space, Proceedings of the Third Space Congress, Cocoa Beach, Fla., March 7-10, 1966, pp. 173-184.

83. Merrill, G. L., and J. B. Starr. Fluidic Temperature Control System for Liquid-Cooled Space Suits, NASA-CR-108330, NAS9-8249, Honeywell, Inc., Minneapolis, Minn., 1969.

84. Mills, E. S. "Spacesuit Systems and Penalties for Interplanetary Missions", Journal of Spacecraft and Rockets, Vol. 3, December 1966, pp. 1738-1744.

85. Molesko, N. Some Design Considerations for Manned Life Support Facilities on the Lunar Surface, Report No. GDA-REL-R-050, General Dynamics/Astronautics, San Diego, Calif., August 1961.

86. Myers, D. A., W. J. O'Reilly, and P. D. Peterson. Portable Environmental Control System, NASA-CASE-XMS-09632-1, U.S. Patent #3,5000,827, Garrett Corp., Los Angeles, Calif., 1970.

87. Myers, D. A., and H. J. Richter. An Approach for the Improvement of EVA/IVA Fluid Umbilical Characteristics, AAS Paper 69-470, Martin Marietta Corp., Denver, Colo., June 1969.

88. Naab, C. Space Suit Ventilation Values, Final Report, NASA-CR-101936, Carleton Controls Corp., East Aurora, N.Y., 1969.

89. NASA: Guidelines for EVA Development, NASA-TM-X-62554, Manned Spacecraft Center, Houston, Tex., 1967.

90. Nelson, W. G. Gemini Extravehicular Suit Pressurization Ventilation Test Series, NASA-CR-65559 SS3/35, Rev. 1, NAS9-2412, AiResearch Mfg. Co., Los Angeles, Calif., June 19, 1964.

91. Normyle, W. J. "Lunar Astronauts to Use New Oxygen Pack", Aviation Week and Space Technology, Vol. 88, June 3, 1968, pp. 76, 77, 81, 83, 86, 87.

92. North American Rockwell Corp.: Extravehicular Engineering Activities/ EVEA/Program Requirements Study, Vol. 2 - Detailed Technical Report, Final Report, NAS8-18128, NASA-CR-95913, Downey, Calif., May 6, 1968.

93. Oreilly, W. J. Project Gemini-Extravehicular Life Support System (ELSS), Final Report, NASA-CR-92066, AiResearch Mfg. Co., Los Angeles, Calif., January 30, 1964 - March 31, 1967.

94. Perry, David G., Leroy R. Curry, Jr., Donald B. Hanson, and George B. Towle. A Study of Extravehicular Protective Garments, Contract No. AF 33(615)-1780, United Aircraft Corp., Windsor Locks, Conn., February 1966.

95. Public Health Service: Reduction of Microbial Dissemination, Germicidal Activity of Ethylene Oxide, Reduction of Microbial Contamination on Surfaces, Evaluation of Leakage of Microbial Contamination from Space Suits, Summary Report No. 7, NASA-CR-75733, N66-28455, Washington, D.C., May 1966.

96. Reid, R. C., and D. L. Richardson. Portable Life Support Systems for Extravehicular Activities, AICHE Paper 42C, Massachusetts Institute of Technology, Cambridge, Mass., December 1968.

97. Richardson, D. L. Development of an Improved Extravehicular Space Suit Thermal Insulation, Final Report, NASA-CR-101948, NAS9-7519, Arthur D. Little, Inc., Cambridge, Mass., 1968.

98. Richardson, David L. Research to Advance Extravehicular Protective Technology, Contract No. AF 33(615)-2963, Arthur D. Little, Inc., Cambridge, Mass., April 1967.

99. Richardson, D. L. Study and Development of Materials and Techniques for Passive Thermal Control of Flexible Extravehicular Space Garments, AMRL-TR-65-156, AD-624886, Arthur D. Little, Inc., Cambridge, Mass., September 1965.

100. Richardson, D. L. Techniques and Materials for Passive Thermal Control of Rigid and Flexible Extravehicular Space Enclosures, Final Report, February 1966 - May 1967, AMRL-TR-67-128, AD-666940, Arthur D. Little, Inc., Cambridge, Mass., December 1967.

101. Roth, E. M. Rapid/Explosive/Decompression Emergencies in Pressure-Suited Subjects, NASA-CR-1223, NASR-115, Lovelace Foundation for Medical Education and Research, Albuquerque, N. Mex., November 1968.

102. Roth, H. P. "Work and Thermal Loads on Men Working in Space Suits", N66-17395, A Collection of Papers on Spacesuits and Human Performance, Chrysler Corp., New Orleans, La., August 16, 1965.

103. Samson, J. H. Extravehicular Engineering Activities/EVEA/Program Requirements Study - SRT/ART Analysis Final Report, NAS8-18128, NASA-CR-98090, North American Rockwell Corp., Long Beach, Calif., September 1968.

104. Savitsky, Yu. Spacesuits--Breathing, Ventilation, Pressure, and Decompression, FTD-TT-64-134/1 & 2 & 4, AD-435997, Air Force Systems Command, Wright-Patterson AFB, Ohio, March 26, 1964.

105. Seale, L. M.: EVA Space Missions - An Overview of the Requirements, National Conference on Space Maintenance and Extravehicular Activities, March 1-3, 1966.

106. Seeler, H. W. "Complete Emergency Life Sustaining System for Spacecraft", Aerospace Medicine, Vol. 35, January 1964, pp. 37-40.

107. Shivers, R. W. "Radioisotope Survival Suit Heater", The Second International Symposium on Nucleonics in Aerospace, Columbus, Ohio, July 12-14, 1967, pp. 194-199.

108. Shlosinger, A. P. Heat Pipe Devices for Space Suit Temperature Control, Research Report, June 30, 1966 - September 1, 1968, NASA-CR-1400, NAS2-3817, TRW Systems Group, Redondo Beach, Calif., 1969.

109. Shlosinger, A. P. "Heat Pipes for Space Suit Temperature Control", Aviation and Space, ASME Proceedings of the Annual Aviation and Space Conference, Beverly Hills, Calif., June 16-19, 1968, pp. 644-648.

110. Shlosinger, A. P. Study of Passive Temperature and Humidity Control Systems for Advanced Space Suits, Final Second Phase Report, September 2, 1967 - September 1, 1968, NASA-CR-73270, NAS2-3817, TRW Systems Group, Redondo Beach, Calif., November 1968.

111. Shlosinger, A. P. Study of Passive Temperature and Humidity Control Systems for Advanced Space Suits, Interim Report, July 1, 1966 - September 1, 1967, NASA-CR-73168, NAS2-3817, TRW Systems Group, Redondo Beach, Calif., September 1967.

112. Schlosinger, A. P. Techniques for Excess Metabolic Heat Rejection from the Outside Surfaces of Protective Suits. NAS2-3817, TRW Systems Group, Redondo Beach, Calif., 1970.

113. Shlosinger, A. P., and W. Woo. Feasibility Study of Integral Heat Sink Space Suit Concepts, NASA-CR-63399, Northrop Space Labs, Hawthorne, Calif., May 1965.

114. Starr, J. B. Fluidic Temperature "Control for Liquid-Cooled Space Suits", NASA Ames Research Center Portable Life Support Systems, N70-28501, 1970, pp. 179-189.

115. "Three-Man Spacesuit Ventilator", Compressed Air, Vol. 69, December 1964, pp. 22-23.

116. Troutman, S. J., Jr., and P. Webb. Automatic Control of Water Cooled Suits from Differential Temperature Measurements, Final Report, NASA-CR-86244, NAS12-682, Webb Associates, Yellow Springs, Ohio, 1969.

117. Tucker, E. M. Space Suit Heat Exchanger, U.S. Patent #3,425,487, NASA Manned Spacecraft Center, Houston, Tex., 1969.

118. Turnbow, F. J. Measurements Report--Thermal Porperty Measurements of Manned Spacecraft Center Spacesuit Materials, NASA-CR-92133, NAS9-3670, TRW Systems, Redondo Beach, Calif., May 1968.

119. Umanskii, S. P. Equipment for Aviators and Cosmonauts. Moscow: Voennoe Izdatel'Stvo Ministerstva Oborony SSSR (in Russian), 1967.

120. Van Schaik, Peter N., and Leonard M. Seale. Space Extravehicular Operations: A review of the Requirements and Alternate System Approaches, Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 1966.

121. Webb, P. Automatic Cooling--Strategies, Designs, and Evaluations, NASA Ames Research Center Portable Life Support Systems, N70-28501, 1970, pp. 159-177.

122. Webb, P. Dissociation of Heat Production and Heat Loss During Changing Activity, Webb Associates, Yellow Springs, Ohio, 1966.

123. Woo, W. Study of Passive Temperature and Humidity Control Systems for Advanced Space Suits, Materials Research Report, July 1, 1967 - September 1, 1968, NASA-CR-73271, NAS2-3817, TRW Systems Group, Redondo Beach, Calif., November 1968.

124. Yefimyev, A. "Walking Above the Earth", Nauchn.-Tekn. Obshchestva SSSR/Moscow/, No. 5, 1965, pp. 6-8, (Translation) Foreign Technology Div., Wright-Patterson AFB, Ohio, March 8, 1967.

125. Young, L. R. Life Support in Unusual Environments, Semiannual Status Report, NASA-CR-107451, Massachusetts Institute of Technology, Cambridge, Mass., November 1969.

BIBLIOGRAPHY OF CREW PROTECTIVE SYSTEMS

CREW PROTECTIVE SYSTEMS
(SPACE SUITS)

1. Adey, W. R., J. Hanley, R. T. Kado, and J. R. Zweizig. "EEG Electrode-Amplifier Harness", Electroencephalography and Clinical Neurophysiology, Vol. 30, February 1971, pp. 147-150.

2. Albright, M., I. Axelrod, and G. Frankel. "Manned Chamber Testing of the Apollo Prototype Space Suit", Journal of Spacecraft and Rockets, Vol. 2, September-October 1965, pp. 822-824.

3. Albright, M., I. Axelrod, and G. Frankel. "Manned Chamber Testing of the Apollo Prototype Space Suit", AIAA Space Simulation Testing, Pasadena, Calif., November 16-18, 1964, pp. 45-51.

4. Aldrin, E. E., Jr. "Summary of Gemini Extravehicular Activities", Technical Review, Vol. 8, No. 4, 1967, pp. 259-289.

5. Annis, J. F., S. J. Troutman, Jr., and P. Webb. "Automatic Cooling in Water Cooled Space Suits", Aerospace Medicine, Vol. 41, March 1970, pp. 269-277.

6. Annis, J. F., and P. Webb. The Principle of the Space Activity Suit, NAS1-6872, NASA-CR-973, Webb Associates, Yellow Springs, Ohio, December 12, 1967.

7. AiResearch Manufacturing Division: Advanced Extravehicular Space Suit (AES), Final Report, Contract No. NAS9-7555, Los Angeles, Calif., August 17, 1970.

8. AiResearch Manufacturing Co.: Torso-Limb Assembly (TLA) for Advanced Extravehicular Space Suit (AES), Master End Item/Contract End Item Detail Specification (Prime Equipment), Part I, MEI/CEI No. 958567A, Contract No. NAS9-7555, January 15, 1970.

9. Archibald, E. R. "A Review of Some Recent and Current Exploratory Development Efforts in Pressure Suit Technology", N68-24882, AGARD Behavioral Problems in Aerospace Medicine, October 1967.

10. Barnes, S. "Space Suit Progress", Machine Design, Vol. 37, February 4, 1965, pp. 100-105.

11. Barnes, S. "Space Suit Progress, Part II--Hot Stunt Men and Hydraulic Stand-ins", Machine Design, Vol. 37, February 18, 1965, pp. 100-163.

12. Barthlome, D. E. The Equipotential Space Suit Design Concept and Its Application to the Space Suit Elbow Joint, NASA-TN-D-5221, Langley Research Center, Langley Station, Va., May 1969.

13. Barthlome, D. E. Equipotential Space Suit, U. S. Patent #4,534,406, NASA-CASE-LAR-10007-1, Langley Research Center, Langley Station, Va., 1970.

14. Bell, L. E., R. M. Machell, J. W. Prim, III, and N. P. Shyken. "Summary of Gemini Extravehicular Activity", N68-14951, Gemini Summary Conference, Manned Spacecraft Center, Houston, Tex., July 1967, pp. 127-146.

15. Bevans, J. T. The Solar Reflectance and/or Hemispherical Emittance of Selected Space Suit Materials, NASA-CR-65244, NAS9-3684, TRW Systems Group, Redondo Beach, Calif., July 15, 1965.

16. Bilski, R. S., J. N. Deyo, and J. L. Klann. Integration of an Isotope Brayton Power System with a Life Support System, NASA Lewis Research Center, Cleveland, Ohio, September 1970.

17. Bitterly, J. G. Evaporative Cooling Garment System (ECGS) Part 2, Final Report, NASA-CR-92333, MDAC-62367, McDonnell Douglas Co., Huntington Beach, Calif., September 1968.

18. Bixler, H. J., A. S. Hoffman, L. A Spano. "New Polymer Material Holds Key to Pervaporative Space Suit Cooling", Space/Aeronautics, Vol. 48, pp. 107, 108, 110, 113.

19. Blockley, B. V., and S. L. Friedlander. Preliminary Evaluation Test of the Langley Cardiovascular Conditioning Suit Concept, NASA-CR-1206, NAS1-6004, Webb Associates, Malibu, Calif., December 1968.

20. Boscola, Edward J., Alan S. Hellman, Gary L. Kellett. Development, Test and Evaluation of Integrated Capsular Physiological Protective Garment, Rept. No. NAEC-ACEl-539, Naval Air Engineering Center, Philadelphia, Pa., November 1966.

21. Burggraf, O. R. Analysis of Large Bending Deformations of a Filamentary Tubular Shell Typical for Pressure Constraint Components of Space Suits, NASA-CR-1507, ARC-R-331, Astro Research Corp., Santa Barbara, Calif., 1970.

22. Burns, F. T., M. W. Horton, H. J. McMann, and E. M Tucker. "Life Support Systems for Extravehicular Activity", Gemini Summary Conference (see N68-1494105-30/pp. 67-77), NASA Manned spacecraft Center, Houston, Tex., 1967.

23. Burns, M., A. Marcum, and J. Slowik. Exploratory Development of Partial Pressure Helmet and Mobility Joints for Emergency Pressure Suit Outfits, Final Report, IIT Research Inst., Chicago, Ill., June 1, 1969-August 31, 1970.

24. Callin, G. D., and C. Kaufman. Physiological Basis for a Passive Extravehicular Thermal Control System, Report No. AMRL-TR-66-47, Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, November 1966.

25. Cernan, E. A., H. A. Ray, Jr., D. C. Schultz, and A. F. Smith. Body Positioning and Restraints During Extravehicular Activity, N68-14948, NASA Manned Spacecraft Center, Houston, Tex., 1967.

26. Chambers, A. B. "Controlling Thermal Comfort in the EVA Space Suit", ASHRAE Journal, Vol. 12, March 1970, pp. 33-38.

27. Copeland, R. J., F. H. Goodnight, and E. G. Lipnicky. "Unmanned Thermal Performance Evaluation of a Gemini Extravehicular Space Suit", NASA-CR-65935, Vol. 1, Test Report, Gemini Bravo Test Series Space Environment Simulator Test, LTV Aerospace Corp., Dallas, Tex., July 7, 1965.

28. Correale, J. V., and W. W. Guy. "Space Suits", Space World, Vol. A-1, September-October 1963, pp. 16-18.

29. Correale, J. V., and W. W. Guy, "Space Suits, Part II", Space World, Vol. A-2, November-December 1963, pp. 32-35.

30. Correale, J. V., R. S. Johnston, and M. I. Radnofsky. Space Suit Development Status, NASA-TN-D-3291, Manned Spacecraft Center, Houston, Tex., February 1966.

31. Curtis, D. L. "Open-Loop Portable Life Support System Lightens Crew Load", Space/Aeronautics, Vol. 52, December 1969, pp. 68, 69, 71.

32. David Clark Co., Inc.: Pressure Sealing Closure, Final Report, March 15, 1963 - February 28, 1966, NASA-CR-65685, NAS9-1186, Worcester, Mass., February 28, 1966.

33. Dawn, F. S., and W. L. Gill. Burn Rate Testing Apparatus with Photocell for Measuring Flame Propagation Between Two Points on Some Material, U. S. Patent Application #SN-853641, NASA, Manned Spacecraft Center, Houston, Tex., 1969.

34. Distefano, F. J. "The Design of Full Pressure Garments with Respect to Specific Mission Objectives and Environmental Conditions", Institute of Environmental Sciences, Annual Technical Meeting, San Diego, Calif., April 13-15, 1966, pp. 203-208.

35. DuBois, J., F. W. Mazy, W. R. Santschi, C. O. Scott, and D. M. Walton. Moments of Inertia and Centers of Gravity of the Living Human Body Encumbered by a Full-Pressure Suit, Final Report, July-December 1963, AD-609863, North American Aviation, Inc., Los Angeles, Calif., November 1964.

36. Dusablon, Louise V., Ferdinand Volta, Jr., Nathaniel S. Schneider, and Leo A. Spano. Passive Thermal Control Systems for Advanced Space Suit Concepts, Contract No. NASA ORDER-R-135, Army Natick Labs., Mass Clothing and Personal Life Support Equipment Lab., November 1968.

37. Elkins, W. "Hard Shell Suit Performance as it Relates to Space Maintenance and Other Extravehicular Activities", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 5.1.1-5.1.6.

38. Flaherty, R. E. A Study of Low Velocity Impacts Into Thin Sheet Aluminum and Nylon Cloth, NASA-TN-D-6324, Manned Spacecraft Center, Houston, Tex., 1971.

39. Fraser, A. F., and P. R. Preiswerk. Slip Net Mobility Joints for Pressure Suits, Contract No. F33615-67-C-1586, Astro Research Corp., Santa Barbara, Calif., November 1968.

40. French, G., D. L. Richardson, and F. E. Ruccia. Extravehicular Space Suit Thermal Insulation, NAS9-7519, AIAA Paper 70-851, Arthur D. Little, Inc., Cambridge, Mass., June 1970.

41. Fried, E., G. Hieser, R. B. Hobbs, and G. S. Karp. Measurement of Thermal Conductance of Multilayer and Other Insulation Materials, Final Report, NASA-CR-65797, NAS9-3685, General Electric Co., Philadelphia, Pa., September 29, 1967.

42. Fulcher, Clay W. G. Control of a Liquid Cooling Garment for Extravehicular Astronauts by Cutaneous and External Auditory Meatus Temperatures, NAS9-10963, NASA-CR-115122, General Electric Co., Houston, Tex., December 8, 1970.

43. Garrett Corp.: Extravehicular Activity, MS-AP-1222-1, N68-85447, Los Angeles, Calif., 1966.

44. Garrett, John W. Clearance and Performance Values for the Bare-handed and the Pressure-gloved Operator, Report No. AMRL-TR-68-24, Aerospace Medical Research Labs, Wright-Patterson AFB, Ohio, August 1968.

45. Genin, A. M., and L. G. Golovkin. "Problems of the Prolonged Autonomous Existence of Humans in Spacesuits", Life in Spacecraft, Vol. 5, 17th International Astronautical Congress, Madrid, Spain, October 9-15, 1966, pp. 159-164.

46. Goodman, J. R., and M. I. Radnofsky. "Lunar Surface and Free Space Hazards Relating to Space Suit Design", Journal of Environmental Sciences, Vol. 8, June 1965, pp. 26-31.

47. Goodnight, F. H. Thermal Tests of a Prototype Gemini Extravehicular System, N66-31644, Ling-Temco-Vought, Inc., Dallas, Tex., August 6, 1964.

48. Goodnight, F. H., and T. E. Mouritsen. Unmanned Extravehicular Environments Operation Qualification Test of the Gemini ELSS (Extravehicular Life Support System) Test Plan, NASA-CR-65279, NAS9-3414, Ling-Temco-Vought, Inc., Dallas, Tex., September 10, 1965.

49. Gran, Alfred A., and Ronald Long. Venting Device for Pressurized Space Suit Helmet, U. S. Patent #3,473,165, NASA-CASE-XMS-09652-1, Hamilton Standard, Windsor Locks, Conn., October 21, 1969.

50. Griffin, James B. Feasibility of a Self-Maneuvering Unit for Orbital Maintenance Workers, Contract No. AF336168197, Chance Vought Corp., Dallas, Tex., no date.

51. Hays, E. L. "Space Suits", Manned Spacecraft--Engineering Design and Operation, Paul E. Purser, Maxine A. Faget, and Norman F. Smith (eds.), New York: Fairchild Publications Inc., 1964, pp. 161-168.

52. Hays, E. L., and R. S. Johnston. The Development and Operation of Extravehicular Equipment, Seventh International Astronautical Congress, Madrid, Spain, October 9-15, 1966.

53. Hedge, Jack C. Survey of Thermal Control Techniques for Extravehicular Space Suits, Contract No. AF33(615)-3468, IIT Research Inst., Chicago, Ill., December 1968.

54. Heimlich, P. F., T. W. Herrala, and D. C. Howard. "Integrated Maneuvering and Life Support System Containing Protective Suit, Life Support System, and Maneuvering Unit for Increased EVA Capability", NASA Ames Research Center Portable Life Support Systems, N70-28501, pp. 11-27.

55. Hodge, W. H. Mission D Extravehicular Activity, NASW-417, NASA-CR-96176, Bellcomm, Inc., Washington, D. C., July 1, 1968.

56. Howard, D. C. Integrated Maneuvering Life Support System, Final Report, NASA-TM-X-66902, United Aircraft Corp., Windsor Locks, Conn., May 31, 1968-October 31, 1969.

57. Howard, D. C. Engineering Design Study of a Space Suit With an Integrated Environmental Control System, Final Report, AMRL-TR-68-122, Hamilton Standard, Windsor Locks, Conn., October 1968.

58. Howard, D. C., and R. G. Syversen. Selection of Astronaut Cooling Systems for Extravehicular Space Missions, AIAA Paper 69-617, United Aircraft Corp., Windsor Locks, Conn., June 1969.

59. Iberall, Arthur S. The Use of Lines of Nonextensions to Improve Mobility in Full-pressure Suits, Contract No. AF33-657-10992, Rand Development Corp., Cleveland, Ohio, November 1964.

60. ILC Industries, Inc.: A7LB Pressure Garment Assembly with Integrated Thermal Meteoroid Garment for Apollo Extravehicular Mobility Unit, Contract End Item Specification (Prime Equipment), CEI No. 3001B, Rev. A, Dover, Delaware, January 30, 1970.

61. ILC Industries, Inc.: Model A7L Advanced Extravehicular Pressure Garment Assembly, Unpublished Presentation, 1969.

62. Iribe, P., and J. A. Lieske. "Environmental and Mobility Constraints on the Configuration of a Non-Anthropomorphic Space Suit", N68-18729, National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

63. Iribe, P., and J. A. Lieske. "Extravehicular Environment and Mobility Constraints on the Configuration of an Anthropomorphic Space Suit System", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 5.3.1-5.3.10.

64. Iribe, P., and J. A. Lieske. Study of Extravehicular Protection and Operations, NASA-CR-773, NASA Order R-21-009-00, Johns Hopkins University, Baltimore, Md., June 1967.

65. Jennings, D. C. "Water-cooled Space Suit", Journal of Spacecraft and Rockets, Vol. 3, August 1966, pp. 1251-1256.

66. Jordan, W. D. Design Studies of Exhaust Plume Heating on the Extravehicular Coverall for the MMU Mission, Contract No. Af04(695)-592, Ling-Temco-Vought Inc., Dallas, Tex., August 1965.

67. Johnston, R. S. "The Development of Space Suit Systems", IAF Second International Symposium on Basic Environmental Problems of Man in Space, Paris, France, June 14-18, 1965.

68. Johnston, R. S. Fabric for Micrometeoroid Protection Garment, NASA-CASE-MSC-12109, U. S. Patent #3,563,198, Manned Spacecraft Center, Houston, Tex., 1971.

69. Johnston, R. S. "Flammability Test Methods and Protective Clothing Development", Brooks AFB Conference on Fire Hazards and Extinguishment, N68-18752, May 23, 1967, pp. 168-189.

70. Jones, R. L. Evaluation and Comparison of Three Space Suit Assemblies, NASA-TN-D-3482, Manned Spacecraft Center, Houston, Tex., July 1966.

71. Juster, A. "The Evaluation of Candidate Space Suit Material and Assemblies", Institute of Environmental Sciences, Annual Technical Meeting, Philadelphia, Pa., April 13-15, 1964, pp. 637-640.

72. Kincaide, W. C. "Space Suit for the Moon", Mechanical Engineering, Vol. 87, November 1965, pp. 49-53.

73. Kosmo, Joseph J., and Elton M. Tucker. Extravehicular Tunnel Suit System, U. S. Patent #3,537,668, NASA-CASE-MSC-12243-1, NASA Manned Spacecraft Center, Houston, Tex., September 12, 1969.

74. Kosmo, J. J., and E. M. Tucker. Extravehicular Tunnel Suit System, U. S. Patent #3,537,668, U. S. Patent APPL-SN-857445, NASA Manned Spacecraft Center, Houston, Tex., November 3, 1970.

75. Kouit, B. "The Space Suit", Space/Aeronautics, Vol. 43, June 1965, pp.43-49.

76. Knezek, R. A., and G. B. Whisenhunt. "Thermal Protection System for Extravehicular Space Suits", Technology of Lunar Exploration, Clifford I. Cummings and Harold R. Lawrence (eds.), New York, N. Y.: Academic Press, Inc., 1963, pp. 433-447.

77. Krichagin, V. I. Space Clothing of Subjugators of Outer Space. FTD-TT-65-604/1&4, AD-620099, Air Force Systems Command, Foreign Technology Division, Wright-Patterson AFB, Ohio, June 18, 1965.

78. Laliberte, A. J. Design, Development and Production of Pressure Suit Spectacles- Final Report, NASA-CR-101860, NAS9-8090, Unirus, Inc., Dudley, Mass., July 1, 1969.

79. Litton Systems, Inc.: Torso Limb Assembly (TLA) for Advanced Extravehicular Space Suit (AES), Master End Item/Contract End Item Detail Specification (Prime Equipment), Part I, Performance Design Requirements, CEI No. SD-9, Spec. No. 241901, Contract No. NAS9-7533, February 16, 1970.

80. Loats, H. L., Jr., G. S. Mattingly, and O. F. Trout, Jr. A Water Immersion Technique for the Study of Mobility of a Pressure-suited Subject Under Balanced-gravity Conditions, NASA-TN-D-3054, Langley Research Center, Langley Station, Va., January 1966.

81. Machell, R. M. Summary of Gemini Extravehicular Activity, NASA-SP-149, Manned Spacecraft Center, Houston, Tex., 1967.

82. Mallen, Lloyd. Suiting Up for Space, The Evolution of the Space Suit, New York, N.Y.: The John Day Company, 1971.

83. Maples, H. E., R. E. Sanders, and J. P. Vincent. Engineering and Operational Experiences Related to Lunar-Surface, Thermal-Vacuum Qualifications of the Apollo Extravehicular Mobility Unit, AIAA Paper 69-992, AA/NASA, Manned Spacecraft Center, Houston, Tex., September 1969.

84. Martin Co.: National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966

85. Matrix Research: Selection of Systems to Perform Extravehicular Activities, Man and Manipulator, Final Report, Vol. 2, Contract No. NAS8-24384, Huntsville, Ala., April 9, 1970.

86. McAllum, W. E. Development of Meteoroid Protection for Extravehicular Activity Space Suits, AIAA Paper 69-366, AA/NASA, Manned Spacecraft Center, Space Physics Div., Meteoroid Sciences Branch, Houston, Tex., April 1969.

87. McDonnell Douglas Astronautics Co.: Extravehicular Crew Transfer Test Report, St. Louis, Mo., September 9, 1968.

88. McDonnell Douglas Astronautics Co.: Extravehicular Crew Transfer Test Report, AD-503415 G525, St. Louis, Mo., September 12, 1968.

89. McDonnell Douglas Astronautics Co.: Extravehicular Crew Transfer Test Report, AD-856903L H048, St. Louis, Mo., March 5, 1969.

90. Merrill, G. L., and J. B. Starr. Fluidic Temperature Control for Liquid-Cooled Space Suits, ASME Paper 70-WA/FLCS-19, Honeywell Systems and Research Center, St. Paul, Minn., November 1970.

91. Michael, R. M. Summary of Gemini Extravehicular Activity, (EVA Accomplishments), NASA-SP-149, NASA Spacecraft Center, Houston, Tex., 1967.

92. Mills, E. S. Spacesuit Systems and Penalties for Interplanetary Missions, Douglas Aircraft Co., Santa Monica, Calif., December 1966.

93. Mizen, N. J. "Feasibility of a Wearable Exoskeletal Structure", ASME Winter Annual Meeting, New York, N.Y., Nov. 29 - Dec. 4, 1964, Paper 64.

94. Molesko, Norman M. A Collection of Papers on Spacesuits and Human Performance, Report No. REL-HFG-65-1, Chrysler Corp., New Orleans, La., August 1965.

95. Myers, D. A., and H. J. Richter. An Approach for the Improvement of EVA/IVA Fluid Umbilical Characteristics, Martin Marietta Corp., Denver, Colo., June 1969.

96. Olson, Robert B., John W. Felder, and Charles F. Lombard. Variable Thermal Conductivity Heat Transfer Research for Personal Protective Assemblies, Contract No. AF 33(615)-5109, Northrop Corp. Lab., Hawthorne, Calif., December 1967.

97. Naab, C. Space Suit Ventilation Valves, Final Report, NASA-CR-101936, NAS9-7646, Carleton Controls Corp., East Aurora, N.Y., 1969.

98. NASA: Extravehicular Mobility Unit for Lunar Module Crewman (EMU/LM) Apollo J-Missions, Master End Item Specification Performance/Design and Product Configuration Requirements, CSD-A-1059, Manned Spacecraft Center, Houston, Tex., May 1968.

99. NASA: Guidelines for EVA Development, NASA-TM-X-62554, Manned Spacecraft Center, Houston, Tex., 1967.

100. NASA: Minutes of Meeting 69-3, NASA Committee on Extravehicular Activities, NASA Headquarters, November 4-5, 1969.

101. NASA: Minutes of Meeting 71-1, NASA Committee on Extravehicular Activities, Manned Spacecraft Center, April 30, 1971.

102. NASA: Model A7L Space Suit, Apollo Block II, Contract End Items Familiarization and Operations Manual, Contract No. NAS9-6100, Doc. #8812700149A, November 21, 1968.

103. Skylab Extravehicular Mobility Unit, Master End Item Specification Performance and Design Requirements, CSD-S-014, MSC-02806, Manned Spacecraft Center, Houston Tex., October 6, 1971.

104. Nevins, Ralph G. Proceedings of the Symposium on Individual Cooling, March 17-18, 1969, Contract F44620-68-C-0020, Kansas State University, July 1969.

105. Nicholson, A. N. Anti-G Suit: Research and Development 1962-65, Rept. No. FPRC-MEMO-227, Flying Personnel Research and Development (England), January 1966.

106. Parry, David G., Leroy R. Curry, Donald B. Hanson, and George B. Towle. A Study of Techniques and Equipment for the Evaluation of Extravehicular Protective Garments, Contract No. AF 33(615)-1780, United Aircraft Corp., Windsor Locks, Conn., February 1966.

107. Parin, V. V. Some Medical, Psychophysiological, and Technical Aspects of Space Flight, JPRS-29998, TT-65-30950, Joint Publications Research Service, Washington, D.C., May 11, 1965.

108. Parry, David G., Leroy R. Curry, Jr., Donald B. Hanson, and George B. Towle. A Study of Extravehicular Protective Garments, Contract No. AF 33(615)-1780, United Aircraft Corp., Windsor Locks, Conn., February 1966.

109. Rader, P. J. Variable Flexibility Tether System, Final Report, General Electric Co., Philadelphia, Pa., May 1967 - February 1968.

110. Radnofsky, M. I. Nonflammable Clothing Development Program, NASA-TM-X-60897, Manned Spacecraft Center, Houston, Tex., 1967.

111. Radnofsky, M. I. "Space Suits", International Science and Technology, February 1967, pp. 32-39.

112. Richardson, David L. Techniques and Materials for Passive Thermal Control of Rigid and Flexible Extravehicular Space Enclosures, Contract No. AF 33(615)-3533, Arthur D. Little, Inc., Cambridge, Mass., December 1967.

113. Richardson, D. L. Preliminary Design of an Extravehicular Tunnel-Suit System, Final Report, August 9, 1968 - March 9, 1969, NASA-CR-99603, NASA9-8472, Arthur D. Little, Inc., Cambridge, Mass., March 10, 1969.

114. Richardson, David L. Research to Advance Extravehicular Protective Technology, Contract No. AF 33(615)-2963, Arthur D. Little, Inc., Cambridge, Mass., April 1967.

115. Robertson, W. G., and E. C. Wortz. Evaluation of the Metabolic Cost of Locomotion in an Apollo Space Suit, NASA-CR-102154, NAS9-9459, AiResearch Mfg. Co., Los Angeles, Calif., 1970.

116. Rock, Lee C. Extravehciular Research Model Full Pressure Assembly, Rept. No. AMRL-TR-66-179, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, May 1967.

117. Rock, Lee C. Operational Characteristics of the 1964 Extravehicular Research Model Full Pressure Assembly, Rept. No. AMRL-TR-66-179, Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, May 1967.

118. Roebuck, J. A., Jr. "A System of Notation and Measurement for Space Suit Mobility Evaluation", Human Factors, Vol. 10, 1968, pp. 79-93.

119. Romanov, F. Space Suits, NASA-TT-F-8852, N64-22940, Translated into English from Aviats. I Kosmonaut, Moscow, Vol. 1, January 1964, pp. 52-55.

120. Rosenheck, Allan J. Acoustic Noise Rejection and Absorption Techniques, Contract No. AF 33(615)-2392, CBS Labs., Stamford, Conn., September 1966.

121. Samson, J. H. Extravehicular Engineering Activities/EVEAA/Program Requirements Study - SRT/ART Analysis Final Report, NAS8-18128, NASA-CR-98090, North American Rockwell Corp., Long Beach, Calif., September 1968.

122. Santamaria, Louis J. and Meredith H. Radliff. Physiological Work Loads in Pressure Suited Subjects, Report No. NADC-AC-7103, Naval Air Development Center, Warminster, Pa., March 1971.

123. Sasaki, E. H. Donning and Doffing the "Phase B" Apollo Prototype Space Suit During Zero-Gravity, AD-601250, Aerospace Medical Research Lab., April 1964.

124. Sasaki, E. H. Feasibility of Using Handrails to Move Along a Surface While Weightless, Final Report, June - October 1964, AMRL-TR-65-152, AD-628596, Aerospace Medical Div., Aerospace Medical Research Labs. (6570th), Wright-Patterson AFB, Ohio, August 1965.

125. Savitskiy, Yu. Spacesuits -- Breathing, Ventilation, Pressure, FTD-TT-64-134/1 & 2 & 4, AD-435997, Air Force Systems Command, Wright-Patterson AFB, Ohio, March 26, 1964.

126. Schueller, Otto. An Automatic Analog Breathing System for Multicell Pressure Suits, Report No. AMRL-TR-67-235, Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, March 1969.

127. Seale, L. M.: EVA Space Missions - An Overview of the Requirements. National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

128. Sharp, Earl D. A Comparison of Three Full-Pressure Suits in Terms of Control Activation Time, Rept. No. TR-64-126, Aerospace Medical Lab., Wright-Patterson AFB, Ohio, December 1964.

129. Shlosinger, A. P. Advancements of Space Suit Temperature Control Technology by Application of Modified Heat Pipes, AIAA Paper 69-619, AA/TRW Systems Group, Redondo Beach, Calif., June 1969.

130. Shlosinger, A. P. and W. Woo. Feasibility Study of Integral Heat Sink Space Suit Concepts, NASA-CR-63399, Northrop Space Labs., Hawthorne, Calif., May 1965.

131. Shoenberger, R. W. Investigation of the Effects of Vibration on Dial Reading Performance with a NASA Prototype Apollo Helmet, Final Report, December 1965 - March 1966, NASA-CR-94655; Aerospace Medical Div., Aerospace Medical Research Labs (6570th), Wright-Patterson AFB, Ohio, February 1968.

132. Siegel, Arthur I. and Richard S. Lanterman. Human Engineering Aspects of Control Design for Pressure Suited Operators, Contract No. N156-46918, Applied Psychological Services, Wayne, Pa., May 1967.

133. Snow, W. B., and M. S. Latch. Acoustic Noise Cancelling Techniques for Domed Helmets, Final Report, March 13, 1962 - June 15, 1963, AD-424179, Bissett-Berman Corp., Santa Monica, Calif., August 1963.

134. Snyder, R. E. "Space Suits for Normal and Emergency Space Vehicle Operation", AIAA First Annual Meeting, Washington, D.C., June 29 - July 2, 1964, Paper 64-214.

135. Spano, L. A., and F. Votta, Jr. "Experimental Study of a Passive Thermal Control System for Space Suits", Aerospace Medecine, Vol. 4, April 1969, pp. 372-378.

136. Sutton, James G., Phillip F. Heimlich, and Edward Tepper. Advanced Extravehicular Protective System, Interim Report, NASA-CR-114320, NAS2-6021, Hamilton Standard, Windsor Locks, Conn., May 31, 1971.

137. Swope, R. S. MOL Extravehicular Space Suit Data Book, Contract No. AF 04(695)-469, Aerospace Corp., El Segundo, Calif., November 1964.

138. Taylor, Donald D. Development and Integration of Constant Volume Joints into a Pressurizable Test Garment, Contract No. F33615-67-C-1171, Litton Systems, Inc., Beverly Hills, Calif., December 1968.

139. Tucker, E. M. Space Suit Heat Exchanger, U.S. Patent #3,425,487, NASA Manned Spacecraft Center, Houston, Tex., 1969.

140. Van Schaik, Peter N., and Leonard M. Seale. Space Extravehicular Operations: A Review of the Requirements and Alternate System Approaches, Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 1966.

141. Veghte, James H. Efficacy of Pressure Suit Cooling Systems in Hot Environments, Report No. AMRL-TR-65-58, Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, October 1965.

142. Vykukal, H. C. "Advanced Developments in Hard Space Suit Technology", ASME Transactions, Series B, Journal of Engineering for Industry, Vol. 90, pp. 577-583.

143. Vykukal, H. C. Hard Space Suit, Patent #3,405,406, NASA Ames Research Center, Moffett Field, Calif., 1968.

144. Vykukal, H. C. Space Suit Having Improved Waist and Torso Movement, U.S. Patent Application #SN-21644, NASA-CASE-ARC-10275-1, Ames Research Center, Moffett Field, Calif., 1970.

145. Webb, P. Dissociation of Heat Production and Heat Loss During Changing Activity, Webb Associates, Yellow Springs, Ohio, 1966.

146. Webb, P. "The Space Activity Suit -- An Elastic Leotard for Extravehicular Activity", Aerospace Medicine, Vol. 39, pp. 376-383.

147. Welson and Co., Inc.: Habitability -- Garment Concepts and Engineering Data, Final Report, Contract No. NASA-CR-1150, Hartford, Conn., 1971.

148. Welson and Co., Inc.: Handbook of Garment and Accessory Systems Selection Criteria for a Space Station, NASA-CR-114953, BW-221, 1971.

149. Welson and Co., Inc.: Suit Glove Advanced Thermal Protection Program, Final Report, NASA-CR-114974, BW-250, Hartford, Conn., 1971.

150. Wrede, J. A. Evaluation and Development of Metal Impregnated Fabric, Final Technical Report, NASA-CR-65801, NAS9-7253, Aerojet-General Corp., El Monte, Calif., November 1967.

151. Woo, W. Study of Passive Temperature and Humidity Control Systems for Advanced Space Suits, Materials Research Report, July 1, 1967 - September 1, 1968, NASA-CR-73271, NAS2-3817, TRW Systems Group, Redondo Beach, Calif., November 1968.

152. Yefimyev, A. "Walking Above the Earth" Nauchn, - Tekn. Obshchestva SSSR/ Moscow/, No. 5, 1965, pp. 6-8, (translation) Foreign Technology Div., Wright-Patterson AFB, Ohio, March 8, 1967.

153. Yemelyanov, M. D. Some Lessons Learned from Flight of the Voskhod 2, JPRS-30761, TT-65-31322, Joint Publications Research Service, Washington, D.C., June 23, 1965.

154. Zimmerman, F. J. Meteoroid Threat to Extravehicular Space Suit Assemblies, Final Report, March 1, 1966 - March 1, 1967, AD-691461, IIT Research Inst., Chicago, Ill., 1969.

BIBLIOGRAPHY OF
AIRLOCK AND SUPPORT EQUIPMENT

AIRLOCK AND SUPPORT EQUIPMENT

1. Aero Propulsion Lab. and Archer-Daniels-Midland Co.: Second Aerospace Expandable Structures Conference, Mineapolis, Minn., May 25-27, 1967.

2. Belz, D. J. Status of McDonnell Douglas Thermal Analyses of the Orbital Workshop, NASW-417, NASA-CR-95431, Bellcomm, Inc., Washington, D.C., February 5, 1968.

3. Belz, D. J. Trip Report-Airlock Management Meeting, McDonnell Douglas Corp., St. Louis, Mo., Bellcomm, Inc., Washington, D.C., January 9, 1968.

4. Bendix Corp.: ALSS Payloads, Vol. II, Book 4-Cabin Systems, Final Report, NAS8-11287, NASA-CR-64670, Ann Arbor, Mich., June 1965.

5. Berg, K. R. Design and Construction of an Expandable Airlock, NASA-CR-66709, NAS1-5752, Whittaker Corp., San Diego, Calif., 1968.

6. Blackwell, E. G., and J. E. Crawford. Project AHT Final Report, Space-General Corp., El Monte, Calif., December 14, 1965 - December 14, 1966.

7. Bolhofner, K. R. Qualification Test of Hatch Seal Bond, Final Report, NAS9-170, NASA-CR-91833, McDonnell Aircraft Corp., St. Louis, Mo., September 5-7, 1966.

8. Brook, J. The Density Field Associated with Free-Molecular Effusive Flow from an Annular Ring, RM-4415, Grumman Aircraft Engineering Corp., Bettypage, N.Y., March 1969.

9. Bruchey, W. J., Jr., and H. L. Loats, Jr. A Study of the Performance of an Astronaut During Ingress and Egress Maneuvers Through Airlocks and Passageways, NAS1-4059, NASA-CR-971, Environmental Research Associates, Randallstown, Md., April 1968.

10. Brush, C. E., H. L. Loats, Jr., and G. S. Mattingly. A Study of the Performance of an Astronaut During Ingress and Egress Maneuvers Through Airlocks and Passageways, NASA-CR-66342, Environmental Research Associates, Randallstown, Md., April 30, 1965.

11. Brush, C. E., H. L. Loats, Jr., and G. S. Mattingly. A Study of the Performance of an Astronaut During Ingress and Egress Maneuvers Through Airlocks and Passageways, Vol. 2, Appendix 1, Final Report, Environmental Research Associates, Randallstown, Md., April 31, 1965.

12. Bunley, R. L. Operation and Maintenance Manual for Vacuum and Inbleed Control System, Airlock Control System, Chamber Lines Differential Pressure Control System and Interior Gas Flow Recording System for Altitude Chambers, Final Report, AD-624587, C.G.S. Scientific Corp., Southampton, Pa., October 5, 1965.

13. Byke, R. M., D. E. Charhut, and C. M. McClelland. Design of Space Stations for Low Atmospheric Leakage, McDonnell Douglas Astronautics Co., Huntington Beach, Calif., March 1971.

14. Carden, W. H. Simulated Meteoroid Impact Testing on a Composite Expandable Structure for Spacecraft Airlock Application, Final Report, ARO, Inc., Arnold Air Force Station, Tenn., December 1, 1967 - August 29, 1968.

15. Carlyle, L., F. E. Duskin, and K. G. Englar. "Considerations for Manned Space Vehicle Airlock Design", Advances in the Astronautical Sciences, Vol. 16, Part 1, Western Periodicals Co., 1963, pp. 438-446.

16. Cormier, A., F. Forbes, and L. Jurich. Expandable Airlock Experiment for the Orbital Workshop, IAF Paper SD-49, Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 1968.

17. Cormier, A., F. Forbes, and L. Jurich. Expandable Airlock Experiment for the Orbital Workshop, Goodyear Aerospace Corp., Astronautics Program Dept., Akron, Ohio, October 1968.

18. Cormier, A. W., F. W. Forbes, L. Jurich, G. Reid, and J. Williams. "Expandable Airlock Experiment for the 54B Workshop", N68-27924, AFSC Expandable and Modular Structures Conference, May 1967, pp. 115-143.

19. Counas, G., J. Makowski, and P. Stone. Collective Protection Against CB Agents, Vol. 1, Fourth Bimonthly Progress Report, AiResearch Mfg. Co., Los Angeles, Calif., January 1 - February 28, 1965.

20. Dean, R. D., E. R. Erickson, and R. P. Langan. Airlock Assessment and Ergometric Evaluation Under Simulated Weightlessness/Neutral Buoyancy, Final Report, Boeing Co., Seattle, Wash., June - July 1965.

21. Forbes, F. W., V. F. Hribar, L. Jurich, and J. Schofield. "Expandable Structure Concept of Crew Transfer Tunnel for Space Vehicles", N66-27267, Aerospace Expandable Structures, 1966, pp. 1-18.

22. Forbes, F. W., and M. I. Yarymovych. Expandable Structures for Space Applications, AB/USAF Office of Assistant Secretary of the Air Force for Research and Development, Washington, D.C., 1969.

23. Garnett, Robert J., and Roger C. Walker. Pre-Phase I Study for the MOL P-6-Extravehicular Activity (EVA) Experiment, Vol. 1, Technical Report, Contract No. AF 33(615)-2140, LTV Aerospace Corp., Dallas, Tex., December 1964.

24. Hart, R. J., L. J. WalRover, and W. E. Zosky. The Apollo Command Module Side Access Hatch System, North American Rockwell Corp., Downey, Calif., January 1, 1970.

25. Hawkins, R. M., and A. H. McKibbin. Development of Compressor End Seals, Stator Interstage Seals, and Stator Pivot Seals in Advanced Air Breathing Propulsion Systems, Semiannual Report, January 1 - June 30, 1968, NASA-CR-54628, NAS3-7605, Pratt and Whitney Aircraft, East Hartford, Conn., July 1968.

26. Heathcoat, J. P., and R. H. Norton. Thruster Maintenance System, U.S. Patent-Appl.-SN-840176, NASA-CASE-MFS-20325, NAS8-20073, Brown Engineering Co., Huntsville, Ala., July 9, 1969.

27. Heathcoat, J. P., and R. H. Norton. Thruster Maintenance System, U.S. Patent #3,572,610, NASA-CASE-MFS-20325, Brown Engineering Co., Inc., Huntsville, Ala., March 30, 1971.

28. Hoffman, T. L., and L. Jurich. "Concepts and Development of Expandable Manned Space Structures", N68-27919, AFSC Expandable and Modular Structures Conference, May 1967, pp. 23-40.

29. Holmon, E. V. Concealed Hinge Permits Flush Mounting of Doors and Hatches, MSC-623, B66-10336, July 1966.

30. Hough, W. W. Elimination of Capability to Perform Decoupled ATM Mission, Case 620, NASW-417, NASA-CR-73580, Bellcomm, Inc., Washington, D.C. October 29, 1968.

31. Jackson, J. K., and E. C. Thomas. Prediction of Gas Leakage of Environmental Control Systems, B70-10201, Hq-10270, April 1970.

32. Johnson, S. F., and E. O. Roberts. Crew Station Research for Aerospace Vehicles Experiments Performed Under Zero-Gravity, Part 1-Translation and Hatchway Ingress-Egress Techniques, FDFR-TM-64-23, Wright-Patterson AFB, Ohio, July 1964.

33. Judd, J. H. Spacecraft Airlock, U.S. Patent #3,386,685, NASA-CASE-XLA-02050, NASA, Langley Research Center, Langley Station, Va., June 4, 1968.

34. Kleberg, A.G.K., and E. B. Konecci. "Space Flight Safety--Impact of Apollo Accident on Government/Industry Management, Research and Development Safety Program, Escape Technology, and Future Space Programs", N68-27936, AFSC, Expandable and Modular Structures Conference, May 1967, pp. 391-399.

35. Klomp, E. D. "Note on an Aerodynamic Seal", Aeronautical Journal, Vol. 75, January 1971, pp. 53-55.

36. Landholt, L. Dissection of Hatch Actuator Breech Cartridge, P/N A218,10/15-1006, Final Report, McDonnell Douglas Co., St. Louis Mo., February 16, 1967.

37. Loats, H. L., Jr., and G. S. Mattingly. A Study of the Performance of an Astronaut During Ingress and Egress Maneuvers Through Airlocks and Passageways, Final Phase I, NASA-CR-66340, ERA-64-6, Environmental Research Associates, Randellstown, Md., August 31, 1964.

37. Lockheed Nuclear Products: Effect of Nuclear Radiation on Materials at Cryogenic Temperatures, Quarterly Progress Report 5, July - September 1961, NASW-114, N62-11772, Marietta, Ga., 1961.

38. Martin Co.: Design Reference Mission Document Cluster Configuration Mission Flight S-AA-2, Vol. 6 - Alternate Mission Plans and Contingency Planning, NAS8-21004, NASA-CR-106788, Denver, Colo., January 20, 1967.

39. McDonnell Aircraft Corp.: Heat Shield Hatch Acceptance Test for Functional Fit and Temperature, Final Report, REPT-058-ARB.04.02, St. Louis, Mo., March 14, 1969.

40. McDonnell Aircraft Corp.: Heat Shield Hatch Appectance Test for Functional Fit and Temperature, Final Report, REPT-058-ARB.40.01, St. Louis, Mo., December 31, 1968.

41. McDonnell Douglas Astronautics Co.: Extravehicular Crew Transfer Test Report, St. Louis, Mo., September 9, 1968.

42. McDonnell Douglas Co.: Gemini B Large Pressure Bulkhead Hatch Element Strength Verification Test, Final Report, St. Louis, Mo., July 19, 1968.

43. McDonnell Douglas Astronautics Co.: Gemini B Oxygen Safety Study, Vol. 9 - Testing, St. Louis, Mo., May 15, 1967.

44. McDonnell Douglas Co.: Heat Shield Hatch Mechanism - Simulated Attiude and Temperature Functional Test Final Report, REPT-058-ARB.04, St. Louis, Mo., August 16, 1968.

45. McDonnell Douglas Co.: Hatch Actuator Breech Combustible Material Evaluation, Final Report, St. Louis, Mo., August 28, 1968.

46. Miller, D. G. AAP Airlock Module Coolant, Debris Collection and Sonic Flow Limiter Noise, NASW-417, NASA-CR-100310, Bellcomm, Inc., Washington, D. C., December 5, 1968.

47. Miller, D. G., and G. M. Yanizeski. Trip Report - Discussion of AM and CSM Thermal Control Systems at MSC, Bellcomm, Inc., Washington, D. C., September 10, 1968.

48. NASA: Manned Space Flight Report Actions Taken as a Result of the AS-204 Accident, NASA-TM-X-61455, NASA, Washington, D.C., 1968.

49. Neary, K. J. Inflatable O-Ring Seal Would Ease Closing of Hatch Cover Plate, MSC-740, B66-10385, August 1966.

50. Nicklayen, A. Assembler -- The Future Profession of an Astronaut, NASA-CR-92593, NAS7-100, Terra-Space Corp., Malibu, Calif., 1967.

51. Olewinski, W., T. Marion, L. Wilder, R. Knipe, and N. Belasco. Research Study of the Biomedical Aspects of the Proposed Aerospace Environmental Chamber, Contract No. AF 40 600 1012, General Electric Co., Philadelphia, Pa., December 1963.

52. Petzold, M. F. Operation and Service Manual for Hatch Actuator Test Fixture 52E040094, McDonnel Douglas Co., St. Louis, Mo., November 20, 1967.

53. Powers, J. W. Multiple Docking Adapter Thermal Control System, NASW-417, NASA-CR-73531, Bellcomm, Inc., Washington, D. C., September 30, 1968.

54. Reid, G. B., and D. R. Seger. "Zero-g Simulation and Its Relationship to Space Experiments", N68-27931, AFSC Expandable and Modular Structures Conference, May 1967, pp. 285-298.

55. Sakolosky, J. J. Description of Molecular Sieve Carbon Dioxide Removal Systems, NASW-417, NASA-CR-100267, Bellcomm, Inc., Washington, D. C., December 20, 1968.

56. Schneider. Elastic Seal Stress Analysis Program, G-MSC-G116, UNIVAC 1108, NASA Manned Spacecraft Center, Houston, Tex., September 1970.

57. Simons, John C., Dieter E. Walk, and Charles W. Sears. Mobility of Pressure-Suited Subjects Under Weightless and Lunar Gravity Conditions, Report No. AMRL-TR-65-65, Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, August 1965.

58. Steele, J. L., and D. A. Vaughn. "Portable, Multiunit Low-Pressure Chamber with Locks", Journal of Applied Physiology, Vol. 26, April 1969, pp. 492-493.

59. Sturgill, R. "Critical Analysis of the Role of Airlocks", Collective Protection Against CB Agents, Vol. 1, AiResearch Mfg., Co., Los Angeles, Calif., February, 1965, pp. 183-195.

60. Thornton, R. M. Evaluation Test Report for Tantalum Wet Slug Capacitors, Gulton Industries, Inc., Hawthorne, Calif,, July 31, 1967.

61. Trout, O. F., Jr. An Investigation of Leakage of Large-Diameter O-Ring Hatches, NASA-TN-D-4394, Langley Research Center, Langley Station, Va., March 1968.

62. Trout, O. F., Jr. Vacuum Leakage Test of a Simulated Lightweight Spacecraft Air Lock, NASA-TN-D-5864, NASA Langley Research Center, Langley Station, Va., July 1970.

63. Tweedie, T. C., Jr. Pressure in the Saturn 1 Workshop During Orbital Storage, NASW-417, NASA-CR-106418, Bellcomm, Inc., Washington, D.C., July 3, 1969.

64. Von Beckh, H. J. "Protection Against Accidental Decompression by Compartmentalization of Spacecraft and Aircraft", Aerospace Medicine, Vol. 41, February 1970, pp. 143-153.

65. Von Beckh, H. J. Protective Measures Against Accidental Decompression in Space and Atmospheric Flight, Aerospace Medical Div., Aeromedical Research Lab., Holloman AFB, N. Mex., March 1970.

66. Van Der Bur, J. "Investigation of Protective Materials", Collective Protection Against CB Agents, Vol. 1, AiResearch Mfg., Co., Los Angles, Calif., February 1965, pp. 225-234.

67. Weygand, A. G. Discussion of Proposed Changes to the Communications Systems of the AM and ATM in AAP, NASW-417, NASA-CR-107359, Bellcomm, Inc., Washington, D. C., October 1969.

68. Williams, J. G. "Development of an Expandable Airlock Utilizing the Elastic Recovery Principle", AF Systems Command 2D Aerospace Expandable Structures Conference, March 1966, pp. 467-496.

69. Withee, W. W. Study for Basic Subsystem Module Preliminary Definition, Vol. 3 - 1971 Configuration, Final Report, NAW9-6796, NASA-CR-65825, General Dynamics/Convair, San Diego, Calif., October 1967.

70. Woller, J. A. Evacuation Port Seal, Patent #3,415,032, NASA MSFC, Huntsville, Ala., 1968.

71. Zoszak, J. Coupling and Assembly of Orbiting, Pressurized Modules, Lockheed Aircraft Corp., Lockheed Missiles and Space Co., Research Laboratories, Palo Alto, Calif., 1963.

BIBLIOGRAPHY OF CREW AND CARGO TRANSFER SYSTEMS

1. Adams, D. M., L. M. Hunt, and A. E. Wudell. Integrated Maneuvering and Life Support System Simulation, Final Report, NASA-CR-99656, Martin Co., Denver, Colo., April 1969.

2. Adams, C. R., and G. Hanff. "Some Human Factors Considerations for Orbital Maintenance and Materials Transfer", Aerospace Medicine, Vol. 36, March 1965, pp. 223-230.

3. Adams, J. J. A Simplified Method for Measuring Human Transfer Functions, NASA-TN-D-1782, 1963.

4. Anon.: "Extendible Booms in Space", Engineering, Vol. 202, August 1966, pp. 247.

5. Ashkenas, I. L., et. al. "Design Implications of the Human Transfer Functions", Aerospace Engineering, September 1962, pp. 76-77 and 144-147.

6. Automation and Remote Control: "Experimental Analysis of Time-Variation of the Human Operator's Transfer Function", Butterworth Pub., London, 1961, pp. 629-635.

7. Beasley, G. P. Extravehicular Maneuvering in Space--Investigation of a Simplified Maneuvering Technique, AA/NASA, Langley Research Center, Hampton, Va., 1966.

8. Beggs, J. C. "Design and Development of the Apollo Extravehicular Mobility Unit", New York Academy of Sciences, Annals, Vol. 134, November 22, 1965, pp. 441-451.

9. Bell, L. E., R. M. Machell, J. W. Prim, and N. P. Shyken. "Summary of Gemini Extravehicular Activity", N68-14951, Gemini Summary Conference, Manned Spacecraft Center, Houston, Tex., July 1967, pp. 127-146.

10. Bird, J. D., R. F. Hellbaum, and D. F. Thomas, Jr. An Extravehicular Space Locomotion Device, NASA-TN-D-3809, NASA Langley Research Center, Langley Station, Va., March 1967.

11. Blackmer, R. H. Remote Manipulators and Mass Transfer Study, Final Technical Report, February 1967 - May 1968, Report No. S-68-1169, General Electric Co., Schenectady, N. Y., November 1968.

12. Blackmer, R. H. Remote Manipulators and Mass Transfer Study, Final Technical Report, February 1967 - May 1968, Report No. S-68-1169, General Electric Co., Schenectady, N. Y., November 1968.

13. Blakely, R. L., and B. N. Taylor. Computer Analysis Techniques for Spacecraft Adsorption Beds, McDonnell Douglas Corp., Huntington Beach, Calif., 1969.

14. Breul, H. T., and T. L. Keller. Hands-Free Precision Control for EVA, National Conference on Space Maintenance and Extravehicular Activity, Las Vegas, Nev., August 6-8, 1968.

15. Breul, H., T. Keller, J. Ohagan, and R. Weston. Hands-Free Precision Control for EVA--An Exploratory Study, NAS2-2595, NASA-CR-73105, Grumman Aircraft Engineering Corp., Bethpage, N. Y., January 1967.

16. Browne, L., G. Lamb, W. Robertson, W. Schreck, and E. C. Wortz. A Study of Astronaut's Extravehicular Work Capabilities in Weightless Conditions, NAS1-7571, NASA-CR-1334, Garrett Corp., Los Angeles, Calif., May 1969.

17. Bryan, H. R., and L. E. Bustle, Jr. The Digital Computer Program AMUSIN--An Analysis of the Dynamic Performance of an Astronaut Maneuvering System, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, June 1967.

18. Cernan, E. A., H. A. Ray, Jr., D. C. Schultz, and A. F. Smith. Body Positioning and Restraints During Extravehicular Activity, N68-14948, NASA Manned Spacecraft Center, Houston, Tex., 1967.

19. Chang, D. C., and C. W. Harrison, Jr. "On the Pulse Response of a Flush -Mounted Coaxial Aperture", Transactions on Electromagnetic Compatibility, Vol. EMC-13, Boulder, Colo., February 1971, pp. 14-18.

20. Collins, M., W. C. Huber, H. I. Johnson, and E. H. White, II. Extravehicular Maneuvering About Space Vehicles, N68-14949, NASA Manned Spacecraft Center, Houston, Tex., 1967.

21. Curtis, D. L. "Contingency Transfer System", Aerospace Medicine, Vol. 41, August 1970, pp. 946-947.

22. Donahue, J. W. "Experiment D-12, Astronaut Maneuvering Unit", N67-16027, NASA, Washington Manned Space-Flight Expt., Gemini IX Mission, November 1, 1966.

23. Eakin, G. J., and G. F. Campbell. Human Operator Transfer Function Investigation, Rept. TE-665-F-5, Contract No. AF33(038)-9200, Cornell Aeronautical Lab., Buffalo, N. Y., 1957.

24. Faget, M. A., and R. E. Smylie. Apollo Life-Support and Protective Systems, NASA Manned Spacecraft Center, Houston, Tex., October 1969.

25. Ferrel, R., et al. "Report of Manipulator Control Work at the Massachusetts Institute of Technology", AEC Proceedings of the 1964 Seminar on Remotely Operated Spec. Equipment, Vol. 2, pp. 86-97.

26. Ferrell, W. R. "Remote Manipulation with Transmission Delay", IEEE Trans. Human Factors Electronics, September 1965, pp. 24-32.

27. Fokht, A. S., and A. B. Rubin. "Mathematical Simulation of Closed Ecosystems", Cosmic Research, Vol. 6, April 1968, pp. 239-249.

28. Garrett Corp.: Extravehicular Activity, MS-AP-1222-1, N68-85447, Los Angeles, Calif., 1966.

29. Garnett, R. J., and F. W. Parker. "The Astronaut Maneuvering Unit", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 3.2.1-3.2.18.

30. Garnett, Robert J., and Roger C. Walker. Pre-Phase I Study for the MOL P-6-Extravehicular Activity (EVA) Experiment, Vol. I, Technical Report, Contract no. AF33(615)-2140, LTV Aerospace Corp., Dallas, Tex., December 1964.

31. Givens, E. G., Jr., and W. C. McMillin. Description and Status of DOD Gemini Experiment D-12 Astronaut Maneuvering Unit, Fourth American Institute of Aeronautics and Astronautics, Manned Space Flight Meeting, St. Louis, Mo., paper A66-11613 02-15, October 11-13, 1965.

32. Griffin, J. B. Feasibility of a Self-Maneuvering Unit for Orbital Maintenance Works, Chance Vought Corp., Aironautical Systems Division, Wright-Patterson AFB, Ohio, August 1962.

33. Haines, J. F., A. T. Woodford, B. Abbott, et. al.: Boom Attachment System, DeHavilland Aircraft of Canada Ltd., Technical Report AFAPL-TR-67-14, August 19, 1967.

34. Heimlich, P. F., and T. W. Herrala. Integrated Maneuvering and Life Support System, AMRL-TR-69-41, Hamilton Standard, Windsor Locks, Conn., 1970.

35. Henderson, J. F. "The Estimation of the Transfer Function of a Human Operator by a Correlation Method of Analysis", Ergonomics, Vol. 2, 1959, pp. 274-286.

36. Hodge, W. H. Mission D Extravehicular Activity, NASW-417, NASA-CR-96176, Bellcomm, Inc., Washington, D. C., July 1, 1968.

37. Howard, D. C. Integrated Maneuvering Life Support System Final Report, ASA-TM-X-66902, United Aircraft Corp., Windsor Locks, Conn., May 31, 1968-October 31, 1969.

38. "The Human Transfer Function in Servo Systems", Auto and Manual Control, 1952, pp. 473-494.

39. Iribe, P., and J. A. Lieske. "Environmental and Mobility Constraints on the Configuration of a Nonanthropomorphic Space Suit", N68-18729, National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

40. Iribe, P., and J. A. Lieske. Study of Extravehicular Protection and Operations, NASA-CR-773, NOW-62-0604-C, Johns Hopkins University, Baltimore, Md., June 1967.

41. Ivanov, D. Means of Rescuing a Spacecraft Crew, N69-23348, National Translations Center, John Crerar Library, Chicago, Ill. 60616, translated into English from Aviats. I Kosmonaut, Moscow, No. 2, 1969, pp. 42-43.

42. Jackson, A. "Synthesis of a Quasi-Linear Transfer Function for the Operator in Man-Machine Systems", IRE Wescon Conv. Rec., Pt. 4, 1958, pp. 263-271.

43. Jordan, W. D. Design Studies of Exhaust Plume Heating on the Extravehicular Coverall for the MMU Mission, Contract No. AF04(695)-592, Ling-Temco-Vought Inc., Dallas, Tex., August 1965.

44. Kenner, P. M., and E. Parsons, Jr. Tether-Line Retrieval of Astronauts Under Emergency Conditions, Ling-Temco-Vought, Inc., Dallas, Tex., 1965.

45. Lindemuth, R. W., and J. A. Tieber. An Analysis of the Inertial Properties and Performance of the Astronaut Maneuvering System, GA/PH/65-4, AD-622443, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, August 1965.

46. Machell, R. M. Summary of Gemini Extravehicular Activity, NASA-SP-149, Manned Spacecraft Center, Houston, Tex., 1967.

47. Martin Co.: National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

48. Mayo, A. M. In Space Rendezvous, Rescue and Recovery, Proceedings, American Astronautical Society, Symposium, Air Force Flight Test Center, Edwards AFB, Calif., September 10-12, 1963.

49. McMillian, W. C., and G. M. Monroe. Description of the Astronaut Maneuvering Unit, LTV Aerospace Corp., Astronautics Division, Dallas, Tex., 1967.

50. McDonnell Douglas Astronautics Co.: Extravehicular Crew Transfer Test Report, Report No. H048, AD-856 903L, St. Louis, Mo., March 1969.

51. McDonnell Douglas Astronautics Co.: Extravehicular Crew Transfer Test Report, AD-856875L, G525-ADD-1, St. Louis, Mo., March 1969.

52. McDonnell Aircraft Corp.: Heat Shield Hatch Acceptance Test for Functional Fit and Temperature, Final Report, AD-856656L, Rept.-058-ARB.04.01, St. Louis, Mo., December 31, 1968.

53. McDonnell Douglas Astronautics Co.: Extravehicular Crew Transfer Test Report, St. Louis, Mo., September 9, 1968.

54. McMann, H. J., Jr., L. W. Morar, and C. E. Whitsett, Jr. "Maneuvering-Unit Development Programs", Joint National Meeting of the American Astronautical Society and ORSA, paper no. XIII.E.2, Denver, Colo., June 1969.

55. Mueller, D. D. Long Tetherlines for Orbital Docking or Recovery of Astronaut Operating in Space, AMRL-TDR-62-123, Aerospace Medical Division, Aerospace Medical Research Labs., (6570th), Wright-Patterson AFB, Ohio, November 1962.

56. Myers, D. A., and H. J. Richter. An Approach for the Improvement of EVA/IVA Fluid Umbilical Characteristics, Martin Marietta Corp., Denver Div., Denver, Colo., June 1969.

57. NASA: Apollo Operations Handbook, Extravehicular Mobility Unit, Vol. 1-System Description, CSD-A-789-/1/, Apollo 14, Manned Spacecraft Center, Houston, Tex., June 1970.

58. NASA: Human Transfer Functions in Multi-Axis and Multi-Loop Control Systems, NASA-TN-D-3305, 1966.

59. NASA: Measurements of Human Function with Various Model Forms, NASA-TN-D-2394, 1964.

60. NASA: Measured Human Transfer Functions in Simulated Single Degree-of-Freedom Nonlinear Control Systems, NASA-TN-D-2569, 1965.

61. NASA: MDA External Mobility Aids Evaluation Simulation Test Report, NASA-TM-X-53894, NASA, Marshall Space Flight Center, Huntsville, Ala., September 12, 1969.

62. North American Aviation, Inc.: Astronaut Transfer Operations Study Final Technical Report, NAS8-18123, NASA-CR-78693, Downey, Calif., September 6, 1966.

63. North American Rockwell Corp.: Extravehicular Engineering Activities (EVEA) Program Requirements Study, Appendix A--Transfer, Locomotion and Rescue Experiment Definition, Final Report, NAS8-18128, NASA-CR-96202, Downey, Calif., April 6, 1968.

64. Poli, C. R. A Study of Retrieval Techniques for Tethered Astronauts Technical Report, December 1964 - March 1965, Air Force Systems Command, Wright-Patterson AFB, Ohio, July 1965.

65. Poli, C. R. A Study of Retrieval Techniques for Tethered Astronauts, International Federation of Automatic Control, Second Symposium on Automatic Control in Space, Vienna, Austria, September 4-8, 1967.

66. Power, W. E., and W. E. Bailey. "USAF and American Astronautical Society, Space Rendezvous, Rescue, and Recovery", Advances in the Astronautical Sciences, Vol. 16, Pt. 1, Norman V. Petersen (ed.), 1963, pp. 476-494.

67. Roberts, W. F. Crew Transfer Briefing, Contract No. AF04(695)-469, Aerospace Corp., El Segundo, Calif., September 1964.

68. Schamall, Robert A., and Thomas. J. Wittmann. Design and Operation of a Space Rendezvous Simulator, Contract No. AF33(615)-1125, Technology Inc., Dayton, Ohio, November 1964.

69. Sheffield, K. Orbital EVA, American Astronautical Society and Operations Research Society of America, Joint National Meeting, Denver, Colo., June 17-20, 1969.

70. Sheridan, T. B. "Human Operator's Time-Varying Transfer Characteristics in the Study of Perception and Fatigue", Symposium on Recent Developments in Auto Control, Proceedings, 1960, pp. 161-165.

71. Soshnikov, V. M. "A Relative Motions Model to Describe Cable-aided Cosmonaut-Vehicle Approach", DOKLADY, Vol. 185 (translation), April 11, 1969, pp. 1002-1005.

72. Spady, Amos A., Jr., and W. D. Krasnow. Exploratory Study of Man's Self-Locomotion Capabilities with a Space Suit in Lunar Gravity, NASA-TN-D-2641, 1966.

73. Stewart, R. A. A Study of Dual Purpose Maneuvering Unit, Vol. 1, Final Technical Report, AFPL-TR-67-32, Bell Aerosystems Co., Buffalo, N. Y., March 1966 - March 1967.

74. Stewart, R. A. A Study of Dual Purpose Maneuvering Unit, Vol. 2, Appendices, Final Technical Report, AFAPL-TR-67-22, Bell Aerosystems Co., Buffalo, N. Y., March 1966 - March 1967.

75. Swart, H. "Maneuver Devices for Extravehicualr Activities", Astronomie und Rawm fahrt, No. 6 (in German), 1969, pp. 190-192.

76. Tewell, J. R. "Astronaut Maneuvering Research Vehicle", Martin Marietta Corp., Denver, Colo., Seventh Space Congress, Cocoa Beach, Fla., Vol. 1, April 22-24, 1970, pp. 1-81 to 1-88.

77. Thrasher, J. R. Apollo Extension System (AES) Extravehicular Experiment Definitions Final Report, NASA-CR-90081, Rept.--00.672, LTV Aerospace Corp., Dallas, Tex., August 1, 1965.

78. Tobey, W. H., C. E. Whitsett, Jr., and A. E. Wudell. EVA Maneuvering Unit Comparison, AAS paper 69-516, Martin Marietta Corp., Denver, Colo., June 1969.

79. TRW Systems Group: Astronaut Maneuvering Equipment, Experiment 509, Attitude Control System, NAS9-8166, NASA-CR-11477, Redondo Beach, Calif., November 9, 1970.

80. Van Schaik, P. N. Astronaut Maneuvering Unit 6, Technology, N66-27295, Air Force Systems Command, Wright-Patterson AFB, Ohio, 1966.

81. Van Schaik, P. N. Latest Developments for EVA Space Operations, IAF Paper B-106, Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 10, 1968.

82. Van Schaik, P. N. Multipurpose Propulsion Unit for Space Maintenance, Manned Flight Conference, Dayton, Ohio, Paper No. 65-258, April 21-23, 1965.

83. Van Schaik, Peter N., and Leonard M. Seale. Space Extravehicular Operations: A Review of the Requirements and Alternate System Approaches, Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 1966.

84. Whitsett, C. E. "Experiment M509 Astronaut Maneuvering Equipment", Second National Conference on Space Maintenance and Extravehicular Activity, Paper No. VII.3.1, Las Vegas, Nev., August 1968.

BIBLIOGRAPHY OF EVA WORKSITES AND STABILIZATION

EVA WORKSITES AND STABILIZATION

1. Adams, C. R. "Some Human Factors Considerations for an Orbital Maintenance and Materials Transfer Shuttle", Aerospace Medical Association, 35th Annual Scientific Meeting, Harbour, Fla., Douglas Aircraft Co., Inc., May 1964, pp. 1-3.

2. Adams, C. R., and G. Hanff. "Some Human Factors Considerations for Orbital Maintenance and Materials Transfer", Aerospace Medicine, Vol. 36, March 1965, pp. 223-230.

3. Adlhoch, R. W. Astronaut Tethering and the Gemini Vehicle, Marguardt Corp., Van Nuys, Calif., P. D. Study No. 660, September 21, 1964.

4. Aldrin, E. E., Jr. Summary of Gemini Extravehicular Activities, Technical Review, Vol. 8, No. 4, 1967, pp. 259-289.

5. Anderson, W. W. On Lateral Cable Oscillations of Cable-Connected Space Stations, NASA-TN-D-5107, NASA Langley Research Center, Langley Station, Va., March 1969.

6. Beasley, G. P. Extravehicular Maneuvering in Space-Investigation of a Simplified Maneuvering Technique, AA/NASA, Langley Research Center, Langley Station, Va., 1966.

7. Beasley, G. P. and R. F. Brissenden. "Space Tethering (U)", Conference on Langley Research Related to Apollo Mission, NASA Langley Research Center, Langley Station, Va., 1965, pp. 391-398.

8. Belasco, Norman. Umbilical Lines for Extravehicular Activity, ARS-ASMA Bio-astronautics Conf., Los Angeles, Calif., May 2, 1963.

9. Beletskii, V. V., and E. T. Novikova. "Relative Motion of a Link-Up of Two Objects in Orbit", Cosmic Research, Vol. 7, June 1969, pp. 340-346.

10. Brazell, R. R., E. L. Casco, R. S. French, C. H. Purdy, and G. B. Rozron. Neutral Buoyancy Simulation of Spacecraft Mobility Aids, General Dyanmics/Convair, San Diego, Calif., July 1967.

11. Breul, H. T., and T. L. Keller. Hands-Free Precision Control for EVA National Conference on Space Maintenance and Extravehicular Activity, Las Vegas, Nev., August 6-8, 1968.

12. Cernan, E. A., H. A. Ray, Jr., D. C. Schultz, and A. F. Smith. Body Positioning and Restraints During Extravehicular Activity, N68-14948, NASA Manned Spacecraft Center, Houston, Tex., 1967.

13. Chang, D. C., and C. W. Harrison, Jr. "On the Pulse Response of a Flush-Mounted Coaxial Aperture", Transactions on Electromagnetic Compatibility, Vol. EMC-13, Boulder, Colo., February 1971, pp. 14-18.

14. Christensen, K. K. Study of Umbilical Lines for Extravehicular Operation, Part I, Final Report, IIT Research Inst., Chicago, Ill., February 18 - May 18, 1963.

15. Christensen, K. K. Study of Umbilial Lines for Extravehicular Operation, Part 2, Final Report, IIT Research Inst., Chicago, Ill., July 22 - August 31, 1963.

16. General Dynamics/Convair: Large Space Structure Experiments for AAP, Vol. 3 - Crossed-H Interferometer for Long Wave Radio Astronomy, Final Report, San Diego, Calif., September 15, 1966 - September 1, 1967.

17. Graff, George I. Harness Assembly, Restraint, Crewman, Qualification Test Report, Supplement to Rept. No. IDEP-347.90.00.00-F1-25S, Downey, Calif., January 1967.

18. Gratz, W., J. Lawreance, N. Molesko, and W. Wetherell. "A Study of Telescope Maintenance and Updating in Orbit", SPIE Seminar Proceedings, Vol. 19, Redondo Beach, Calif., 1970.

19. Greensite, A. L., and E. H. Wrench. EVA Stabilization Shoes, General Dynamics Corp., San Diego, Calif., June 1969.

20. Haines, J. F., A. T. Woodford, B. Abbott, et. al.: Boom Attachment System. DeHavilland Aircraft of Canada Ltd., Tech. Report AFAPL-TR-67-14, August 19, 1967.

21. Hodge, W. H. Mission D Extravehicular Activity, NASW-417, NASA-CR-96176, Bellcomm, Inc., Washington, D. C., July 1, 1968.

22. Iribe, P. Orbital Extravehicular Mockup Design, NASA-CR-94927, Applied Physics Lab., Johns Hopkins Univ., Silver Springs, Md., January 1968.

23. Johnson, Lawrence B., Eric Sander, and Stanley Lebow. NASA List of Potential Space Tools and Equipment, NAS2-5073, NASA-CR-1760, Raff Analytic Study Associates, Inc., Silver Springs, Md., May 1971.

24. Kenner, P. M., and E. Parsons, Jr. "Tether-Line Retrieval of Astronauts Under Emergency Conditions", American Institute of Aeronautics and Astronautics, Symposium on Structural Dynamics and Aeroelasticity, Boston, Mass., Paper A65-35608, August 30-September 1, 1965.

25. Kosmo, Joseph J., and Elton M. Tucker. Extravehicular Tunnel Suit System, U. S. Patent #3,537,668, NASA-CASE-MSC-12243-1, NASA Manned Spacecraft Center, Houston, Tex., September 12, 1969.

26. Michael, R. M. Summary of Gemini Extravehicular Activity, (EVA Accomplishments), NASA-SP-149, NASA Manned Spacecraft Center, Houston, Tex., 1967.

27. McDonnell-Douglas Astronautics Co. Extravehicular Crew Transfer Test Report, St. Louis, Mo., September 9, 1968.

28. Mueller, Donald D. An Analysis of the Behavior of Long Tetherlines in Space, Final Report, Aerospace Medical Div. (6570th), Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, November 1962.

29. Mueller, D. D. Long Tetherlines for Orbital Docking or Recovery of Astronaut Operating in Space, AMRL-TDR-62-123, Aerospace Medical Div. (6570th), Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, November 1962.

30. Myers, D. A., and H. J. Richter. An Approach for the Improvement of EVA/IVA Fluid Umbilical Characteristics, Martin Marietta Corp., Denver, Colo., June 1969.

31. NASA: MDA External Mobility Aids Evaluation Simulation Test Report, NASA-TM-X-53894, NASA Marshall Space Flight Center, Huntsville, Ala., September 12, 1969.

32. North American Aviation, Inc.: Harness Assembly, Restraint, Crewman, Report No. SPEC-MC901-0257C, Downey, Calif., May 1965.

33. Poli, C. R. A Study of Retrieval Techniques for Tethered Astronauts, International Federation of Automatic Control, Second Symposium on Automatic Control in Space, Vienna, Austria, September 4-8, 1967.

34. Poli, C. R. A Study of Retrieval Techniques for Tethered Astronauts, Technical Report, December 1964 - March 1965, Air Force Systems Command, Wright-Patterson AFB, Ohio, July 1965.

35. Radar, Philip J. Variable Flexibility Tether System, Final Report, May 1967 - February 1968, Contract No. F33(615)-67-C-1725, General Electric Co., Philadelphia, Pa., September 1968.

36. Sasaki, Edwin H. Feasibility of Using Handrails to Move Along a Surface While Weightless, Report No. AMRL-TR-65-152, Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, August 1965.

37. Seale, L. M. EVA Space Missions--An Overview of the Requirements. National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

38. Soshnikov, V. N. "A Relative Motion Model to Describe Cable-Aided Cosmonaut-Vehicle Approach", Doklady, Vol. 185 (translation), April 1969, pp. 1002-1005.

39. Van Schaik, P. N. Latest Developments for EVA Space Operations, IAF Paper B-106, Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 10, 1968.

40. Van Schaik, Peter N., and Leonard M. Seale. Space Extravehicular Operations: A Review of the Requirements and Alternate System Approaches, Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 1966.

41. Withey, D. J. Variable Flexibility Tether, NAS9-7336, NASA-CR-65966, General Electric Co., Philadelphia, Pa., February 1968.

42. Wuenscher, H. F. Serpentuator Patent, U. S. Patent #3,520,496, NASA-CASE-XMF-05344, NASA Marshall Space Flight Center, Huntsville, Ala., July 14, 1970.

BIBLIOGRAPHY OF EXTERNAL LIGHTING

1. Air Force Systems Command Headquarters: Handbook of Instructions for Aerospace Personnel Subsystem Designers, (HIAPSD), AFSCM-80-3, Washington, D. C., 1966.

2. Allen, L. D., J. V. Correale, W. J. Huffstetler, R. M. Machell, and J. C. Shows. Crew Station and Extravehicular Equipment, NASA Manned Spacecraft Center, Houston, Tex., 1966.

3. Allen, W. H. "Need for Validity in Simulation of the Extra Terrestrial Visual Environment", AIAA Flight Test Simulation and Support Conference, Cocoa Beach, Fla., 1967.

4. Arnold Engineering Development Center: Fifth Annual Symposium on Space Environment Simulation, May 21-22, 1964, (AD-441312), Headquarters, Arnold Air Force Station, Tenn., 1965.

5. Arsyle, E. "Optical Environment in Gemini Space Flights", Science, Vol. 155, January 1967, p. 354.

6. Donaty, L. S. Communications Subsystem Study Guide, Lunar Module LM-3, NAS9-1100, NASA-CR-111289, Grumman Aircraft Engineering Corp., Bethpage, N. Y., August 1968.

7. Emerson Electric Co.: Pegasus-C Coupon Retrieval Procedures and Techniques, Final Report, NAS8-18122, NASA-CR-80307, St. Louis, Mo., October 30, 1966.

8. Finkelstein, S., and E. M. Roth. "Light Environment: A. Visible Light B. Ultraviolet Light", N69-12436, Compendium of Human Responses to the Aerospace Environment, Lovelace Foundation for Medical Education and Research, Albuquerque, N. Mex., November 1968.

9. Gantenbee, R. J. Investigation and Test of Self-Luminous Markers for Aerospace Vehicle Crew Stations, Project No. 1425, Task No. 142501, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, June 1964.

10. Johnson, Lawrence B., Eric Sander, and Stanley Lebow. NASA List of Potential Space Tools and Equipment, NAS2-5073, NASA-CR-1760, Raff Analytic Study Associates, Inc., Silver Springs, Md., May 1971.

11. Kincaid, W. K., Jr. Solar Illumination Simulation, Biotechnology, 55-60, Lockheed Missiles and Space Company, Sunnyvale, Calif., November 1966.

12. Kraus, H., and I. I. Rosenblum. Use of Shadow Map Techniques to Estimate LM/EVA Line-of-Sight, NASW-417, NASA-CR-110487, Bellcomm, Inc., Washington, D. C., June 4, 1970.

13. Lockheed Missiles and Space Co.: Apollo Visual Simulation Studies, LMSC-D080715, Biotechnology Organization, 55-60, Sunnyvale, Calif., March 5, 1969.

14. Lockheed Missiles and Space Co.: Visual Environments Simulations Laboratory, Sunnyvale, Calif., April 1969.

15. Lovelace Foundation for Medical Education and Research: Compendium of Human Responses to the Aerospace Environment, Vol. I, Section 1-6. Contract No. NASr-115, NASA-CR-1205(1), Emanuel M. Roth (ed.), Alburerque, N. Mex., November 1968.

16. Martin Marietta Corp.: Skylab Operations Handbook, Contract No. NAS8-2400, Houston, Tex., July 19, 1971.

17. Marton, T., F. P. Rudek, R. A. Miller, and D. G. Norman. Handbook of Human Engineering Design Data for Reduced Gravity Conditions, Contract No. NAS9-8640 and NAS8-18117, NASA-CR-1726, General Electric Co., Philadelphia, Pa., October 1971.

18. Moran, J. A., and P. R. Tiller. Investigation of Aerospace Vehicle Crew Station Criteria, AFFDL-TDR-64-86, Flight Dynamics Lab., Wright-Patterson AFB, Ohio, July 1964.

19. Morgan, C. T., J. S. Cook, III, A. Chapanis, et al. Human Engineering Guide to Equipment Design. New York, N. Y.: McGraw-Hill, 1963.

20. Ney, E. P., and W. F. Huch. "Optical Environment in Gemini Space Flights", Science, Vol. 153, 1966, pp. 297-299.

21. O'Brien, P. F. "Numerical Analysis for Lighting Design", Illumination Engineering, Vol. 60, April 1965, pp. 169-178.

22. Runyan, T. L., and J. M. Dick. Illumination for Extravehicular Tasks, DAC-P-3876, Douglas Aircraft Co., Inc., Santa Monica, Calif., March 1966.

23. Skolosky, J. J. Apollo Visibility Handbook, NAS9-8166, NASA-CR-92456, Bellcomm, Inc., Washington, D. C., October 4, 1968.

24. Seale, L. M. "EVA Space Missions - An Overview of the Requirements", National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

25. Seidenstein, S., J. A. Janousek, and W. K. Kincaid, Jr. Apollo Illumination Environment Simulation and Study, Vol. III, Contract No. NAS9-7661, Biotechnology Organization, Lockheed Missiles and Space Company, Sunnyvale, Calif., no date.

26. Van Schaik, Peter N., and Leonard M. Seale. Space Extravehicular Operations: A Review of the Requirements and Alternate System Approaches, Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 1966.

27. Warren, W. B. Apollo Mission G - Spacecraft to Spacecraft VHF Coverage, NAS9-8166, NASA-CR-101736, TRW Systems Group, Houston, Tex., June 26, 1969.

28. Wheelwright, Charles D. General Specifications for Spacecraft Lighting and Related Flight Crew Equipment, SC-L-0002, Displays and Controls Section (CD321), NASA Manned Spacecraft Center, Houston, Tex., November 19, 1971.

29. Woodson, W. E., and D. W. Conover. Human Engineering Guide for Equipment Designers, University of California, Berkley, Calif., 1964.

BIBLIOGRAPHY OF COMMUNICATIONS AND TELEMETRY

COMMUNICATIONS AND TELEMETRY

1. Adams, Robert M., Sidney D. Leverett, C. W. Sem-Jacobsen, Robert L. Johnson, and David G. Simons. Medical Education for National Defense --Symposium on Biomedical Monitoring, November 19-20, 1964, AD-467-036, School of Aerospace Medicine, Brooks AFB, Tex., November 1964.

2. Akulinichev, I. T., I. I. Popov, and A. M. Zhdanov. "Problems of Biotelemetry in Long Space Flights", Seventeenth International Astronautical Congress, Vol. 5, Madrid, Spain, October 9-15, 1966.

3. Allen, C. E., J. M. Moore, D. Perron, and J. Prothro. Apollo Communication Systems Performance and Coverage Analysis for Mission Apollo 9, NAS9-9166, NASA-CR-99517, TRW Systems Group, Redondo Beach, Calif., February 14, 1969.

4. Argila, C. A., and J. P. Wilson. Communications Simulation Program/ Comsim/HV008C, Revision, NAS9-8166, NASA-CR-99649, TRW Systems Group, Houston, Tex., April 4, 1969.

5. Bachmann, K., and L. Demling. Biotelemetric, Symposium, Erlangen, West Germany, November 23-30, 1968.

6. Baevskii, R. M., and D. G. Maksimov. Programmed Physiological Measurements and Their Use During 'Voskhod' Space Missions, Report No. SAM-TT-R-946-801, School of Aerospace Medicine, Brooks AFB, Tex., 1968.

7. Beischer, D. E., and W. C. Hixson. Biotelemetry of the Triaxial Ballistocardiogram and Electrocardiogram in a Weightless Environment, NASA-CR-103320, Naval School of Aviation Medicine, Pensacola, Fla., September 8, 1964.

8. Bradford, W. C., and T. V. Chambers. "Manned Spacecraft Data Management Systems", Twenty-first International Astronautical Congress, Konstanz, West Germany, October 4-10, 1970.

9. Bradley, W. E. "Telefactor Control of Space Operations", Astronautics and Aeronautics, Vol. 5, May 5, 1967, pp. 32-38.

10. Brazil, R. S. Space Suit Communication Antenna System, Final Report, NASA-CR-65428, NAS9-4174, Motorola, Inc., Scottsdale, Ariz., June 30, 1966.

11. Carter, H. G., and F. Rachel. "Molecular Helmet Transceiver", 1966 National Electronic Packaging and Production Conference, New York, N. Y., June 21-23, 1966, pp. 647-655.

12. Chervyakova, T. S., and U. V. Tyazhelov. "A Miniature Telemetric Device for Electromyogram Transmission", Space Biology and Medicine, Vol. 2, No. 2, June 27, 1968, pp. 80-84.

13. Cochrun, B. L., and J. S. Rocheford. A Study of Microminiaturized Devices for Bioastronautical Monitoring or Analysis, NASA-CR-98599, Northeastern Univ., Boston, Mass., September 1, 1968.

14. Cribb, Herbert E. Protective Suit Having an Audio Transceiver, U. S. Patent #3,588,359, NASA-CASE-KSC-10164, NASA, John F. Kennedy Space Center, Cocoa Beach, Fla., June 28, 1971.

15. Donaghy, R. E., and J. J. Weippert. Apollo Extravehicular Communications Telemetry Subsystem, Sonex, Inc., Philadelphia, Pa., 1969.

16. Donahue, J. W. "Experiment D-12, Astronaut Maneuvering Unit", N67-16027, NASA, Washington Manned Space-Flight Expt., Gemini IX Mission, November 1, 1966.

17. Ettelson, B., M. Klagsburn, D. Ukkestad, and G. Weltuan. NASA Contributions to Bioinstrumentation Systems--A Survey, Spacelabs, Inc., NASA-SP-5054, 1968.

18. Garnett, Robert J., and Roger C. Walker. Pre-Phase I Study for the MOL P-6-Extravehicular Activity (EVA) Experiment, Vol. I, Technical Report, Contract No. AF33(615)-2140, LTV Aerospace Corp., Dallas, Tex., December 1964.

19. Gibson, R. J., and R. M. Goodman. Space Related Biological and Instrumentation Studies Annual Report, NSR-39-005-018, NASA-CR-119024, A-B2299-5, Franklin Inst., Research Labs., Philadelphia, Pa., March 1971.

20. Glines, A., and J. A. Lazzaro. "Telemetry and Communications to Apollo Flight Controllers", International Foundation for Telemetering, International Telemetering Conference, Los Angeles, Calif., October 13-15, 1970, pp. 528-541.

21. Hanish, H. M. "System Considerations for Biotelemetry from Hostile Environments", Instrument Society of America, Pittsburgh, Pa., 1967, pp. 259-261.

22. Hay, G. M., L. L. Loats, and G. S. Mattingly. Correlation Study of the Simulation of Gemini Extravehicular Activity with Flight Results, NASA-CR-11146, NAS1-7142, Environmental Research Associates, Randallstown, Md., February 1969.

23. Hickman, D. M. "Lunar Surface Suit Telemetry and Voice Communications", IEEE Transactions on Aerospace, Vol. AS-3, June 1965, Supplement, pp. 484-488.

24. Iribe, P., and J. A. Lieske. "Environmental and Mobility Constraints on the Configuration of a Nonanthropomorphic Space Suit", N68-18729, National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

25. Lincoln, R. S., and J. E. Mangelsdorf. An Integrated Approach to Evaluating the Performance Capabilities and Physiological State of Spacecraft Crews, Report No. 6-65-65-15, AD-616-316, Lockheed Missiles and Space Co., Sunnyvale, Calif., April 1965.

26. Lopez, D. S. Trip Report--Comparative Review of Apollo Program Specifications and Contractors Technical Specifications at MSC, Houston, Texas, NASW-417, NASA-CR-73558, Bellcomm, Inc., Washington, D. C., October 16, 1968.

27. Maksimov, D. G. Peculiarities of Physiological Reactions of Pilots During Simulated Egress from a Spacecraft, JPRS-44209, Joint Publications Research Service, Washington, D. C., January 31, 1968.

28. McDonnell Douglas Astronautics Co.: Astronaut/Computer Communication Study, Final Report, NASA-CR-103171, NAS8-25701, Huntington Beach, Calif., March 1971.

29. Meehan, J. P., and R. D. Rader. "Applications of Miniature Biotelemetry Systems to Space Medicine", Instrument Society of America, Pittsburgh, Pa., 1967, pp. 245-250.

30. Murrish, C. H., and G. W. Smith. Apollo Applications Program Crew Motion Experiment Program Definition and Design Development, NAS1-7276, NASA-CR-66599, Martin Co., Denver, Colo., 1967.

31. NASA: Apollo 15 Mission 5-Day Report, NASA-TM-X-67381, NASA Manned Spacecraft Center, Houston, Tex., August 1971.

32. North American Rockwell Corp.: Extravehicular Engineering Activities/ EVEA/Program Requirements Study. Appendix C--Scientific/Technical Experiments Baseline Final Report, NAS8-18128, NASA-CR-95914, Downey, Calif., May 6, 1968.

33. Radio Corporation of America: Extra-Vehicular Communication System Quarterly Progress Report, NAS9-7508, NASA-CR-65997, Camden, N. J., July 27 - October 31, 1967.

34. Seale, L. M. EVA Space Missions--An Overview of the Requirements. National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

35. Selden, R. L. A Possible UHF Backup Communications Between Extravehicular Astronauts on the Lunar Surface and the Earth, NASW-417, NASA-CR-106773, Bellcomm, Inc., Washington, D. C., September 19, 1969.

36. Shafer, W. A. "Telemetry on Man Without Attached Sensors", New York State Journal of Medicine, Vol. 67, November 1, 1967, pp. 2832-2837.

37. Tollison, J. B. "The Apollo Extravehicular Communications System", National Telemetering Conference, Houston, Tex., April 8-11, 1968, pp. 226-230.

38. Twenty-second Meeting of the AGARD Aerospace Medical Panel. AD-660-197, Report No. AGARD-CP-2, Conference Proceedings, Advisory Group for Aerospace Research and Development, Paris, France, September 2-6, 1965.

39. Van Schaik, Peter N., and Leonard M. Seale. Space Extravehicular Operations: A Review of the Requirements and Alternate System Approaches, Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 1966.

40. Weippert, J. J., and R. E. Donaghy. "Apollo Extravehicular Communication and Telemetry Subsystem", International Telemetering Conference, Washington, D. C., September 15-17, 1969, Proceedings, pp. 426-437.

BIBLIOGRAPHY OF DATA/INFORMATION MANAGEMENT SYSTEMS

1. Adams, Robert M., Sidney D. Leverett, C. W. Sem-Jacobsen, Robert L. Johnson, and David G. Simons. Medical Education for National Defense -- Symposium on Biomedical Monitoring, November 19-20, 1964, AD-467-036, School of Aerospace Medicine, Brooks AFB, Tex., November 1964.

2. Adey, W. R., J. Hanley, R. T. Kado, and J. R. Zweizig. "EEG Electrode-Amplifier Harness", Electroencephalography and Clinical Neurophysiology Vol. 30, February 1971, pp. 147-150.

3. Akhutin, V. M. "Principles of Constructing Complexes for Continuous Monitoring of the Human Organism and Automatic Normalization of its State", Bioelectronic Control: Man and Automated Systems, June 21, 1971, pp. 18-32.

4. Akulinichev, I. T., I. I. Popov, and A. M. Zhdanov. "Problems of Biotelemetry in Long Space Flights", Seventeenth International Astronautical Congress, Vol. 5, Madrid, Spain, October 9-15, 1966.

5. Annis, J. F., S. J. Troutman, and P. Webb. "Automatic Cooling in Water Cooled Space Suits", NAWS-1306, NASW-1529, NAS1-2682, Aerospace Medicine, Vol. 41, March 1970, pp. 269-277.

6. Bachmann, K., and L. Demling. Biotelementrie, Symposium, Erlangen, West Germany, November 29-30, 1968.

7. Baevskii, R. M., and D. G. Maksimon. Programmed Physiological Measurements and Their Use During 'Voskhod' Space Missions, Report No. SAM-TT-R-946-0468, AD-672-801, School of Aerospace Medicine, Brooks AFB, Tex., 1968.

8. Beischer, D. E., and W. C. Hixson. Biotelemetry of the Triaxial Ballistocardiogram and Electrocardiogram in a Weightless Environment, NASA-CR-103320, Naval School of Aviation Medicine, Pensacola, Fla., September 8, 1964.

9. Bell, Larry E. EVA Operational Guidelines, EC61-69-0178, NASA Manned Spacecraft Center, 1969.

10. Berry, C. A. "Medical Experience in Manned Space Flight", Aerospace Medicine, Second Edition, 1971, pp. 697-718.

11. Billingsley, D. G., G. F. Hubert, and R. J. Kelly. "A Real-Time Processing System for Determination of Metabolic Rates of a Suited Astronaut", AIAA Paper 69-993, Fourth Space Simulation Conference, Los Angeles, Calif., September 8-10, 1969.

12. Blinov, B. V., I. I. Kasyan, and G. F. Makarov. Changes in Pulmonary Ventilation, Gas Metabolism, and Energy Expenditure During Weightlessness, Eighteenth Congress of the International Astronautical Federation, Belgrade, September 25-30, 1967.

13. Bradford, W. C., and T. V. Chambers. "Manned Spacecraft Data Management Systems", Twenty-first International Astronautical Congress, Konstanz, West Germany, October 4-10, 1970.

14. Celentano, John T. Bioastronautics Laboratory Research Tool Study, Contract No. AF08 606 7039, North American Aviation Inc., El Segundo, Calif., April 1965.

15. Chaffee, W. R., and R. H. Eich. "Hemodynamic Response to G-suit Inflation With and Without Gandlionic Blockage", Aerospace Medicine, Vol. 37, March 1966, pp. 247-250.

16. Chervyakova, T. S., and U. V. Tyazhelov. "A Miniature Telemetric Device for Electromyogram Transmission", Space Biology and Medicine, Vol. 2, No. 2, June 27, 1968, pp. 80-84.

17. Cochrun, B. L., and J. S. Rocheford. A Study of Microminiaturized Devices for Bioastronautical Monitoring or Analysis, NASA-CR-98599, Northeastern Univ., Boston, Mass., September 1, 1968.

18. Dodge, C. H. Soviet Biotechnology and Bioastronautics, Aerospace Technology Division, Library of Congress, Washington, D. C., February 1966.

19. Donaghy, R. E., and J. J. Weippert. Apollo Extravehicular Communications Telemetry Subsystem, Sonex, Inc., Philadelphia, Pa., 1969.

20. Edwards, D. K., III, T. J. Harrington, and E. C. Wortz. "Metabolic Rates in Pressurized Pressure Suits", Aerospace Medicine, Vol. 36, September 1965, pp. 825-830.

21. Ettleson, B., M. Klagsburn, D. Ukkestad, and G. Weltman. NASA Contributions to Bioinstrumentation Systems -- A Survey, NASA-SP-5054, Spacelabs, Inc., 1968.

22. Garnett, Robert J., and Roger C. Walker. Pre-Phase I Study of the MOL P-6-Extravehicular Activity (EVA) Experiment, Vol. I, Technical Report, Report No. ER-00.531 - Vol. 1, AD-463-444, LTV Aerospace Corp., Dallas, Tex., December 1964.

23. Gibson, R. J., and R. M. Goodman. Space Related Biological and Instrumentation Studies Annual Report, NSR-39-005-018, NASA-CR-119024, A-B2299-5, Franklin Inst., Research Labs, Philadelphia, Pa., March 1971.

24. Glines, A., and J. A. Lazzaro. "Telemetry and Communications to Apollo Flight Controlers", International Foundation for Telemetering, International Telemetering Conference, Los Angeles, Calif., October 13-15, 1970, pp. 528-541.

25. Hallin, William P., and Robert C. Steans. Systems and Logistics -- An Analysis of Requisition Transmission Time Performance Reports (Master's Thesis), AD-846-455, Air Force Institute of Technology, School of Systems and Logistics, Wright-Patterson AFB, Ohio, August 1968.

26. Hanish, H. M. "System Considerations for Biotelemetry from Hostile Environments", Instrument Society of America, Pittsburgh, Pa., 1967, pp. 259-261.

27. Hardy, J. C., and R. Lang. Techniques for Physiological Monitoring of Human Performance in a Pressurized Space Suit", AIAA and NASA Third Manned Space Flight Meeting, Houston, Tex., November 4-6, 1964, pp. 118-125.

28. Hewes, Donald E., and A. A. Spady, Jr. Evaluation of a Gravity Simulation Technique for Studies of Man's Self-Locomotion in Lunar Environment, NASA-TN-D-2176, 1964.

29. Hewes, Donald E., and A. A. Spady, Jr. Moon Operations Here on Earth, NASA-RP-207, Reprinted from Astronautics and Aerospace Engineering, 1964.

30. Hewes, Donald E., A. A. Spady, Jr., and R. L. Harris. Comparative Measurements of Man's Walking and Running Gaits in Earth and Simulated Lunar Gravity, NASA-TN-D-3363, 1966.

31. Iampietro, P. F. Use of Skin Temperature to Predict Tolerance to Thermal Environments, Civil Aeromedical Institute, Federal Aviation Administration, Oklahoma City, Okla. 73123.

32. Iribe, P., and J. A. Lieske. Environmental and Mobility Constraints on the Configuration of a Nonanthropomorphic Space Suit, Applied Physics Lab., Johns Hopkins University, Silver Spring, Md., 1966.

33. Jet Propulsion Lab., California Institute of Technology: "Mission Support", The Deep Space Network, Vol. 2, Pasa Dena, Calif., April 15, 1971, pp. 6-41.

34. Keating, John M., James A. Roman, Robert G. Green, and Charles W. Patten. Method and Apparatus for Attaching Physiological Monitoring Electrodes, U. S. Patent #3,426,746, NASA-CASE-XFR-07658-1, General Dynamics, Corp., San Diego, Calif., February 11, 1969.

35. Keele, C. A., and E. Neil. Samson Wright's Applied Physiology, London: Oxford University Press, 1961.

36. Kelley, G. F., D. O. Coons, and W. R. Carpenter. "Medical Aspects of Gemini Extravehicular Activities", Aerospace Medicine, June 1968.

37. Knoop, Patricia A. Development and Evaluation of a Digital Computer Program for Automatic Human Performance Monitoring in Flight Simulation Training, Final Report, January 1966 - January 1967, Report No. AMRL-TR-67-97, AD-675-542, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, August 1968.

38. Kuo, K. L. "Comfort Charts for Man in Gas-Cooled Space Suit and Space Cabin", Thirty-seventh Annual Scientific Meeting, Aerospace Medical Association, Las Vegas, Nev., April 18-21, 1966, Preprint.

39. Letks, Wm. A., A. A. Spady, Jr., and D. E. Hewes. The Problems of Man's Adaptation to the Lunar Environment, National Academy of Sciences, National Research Council Committee on Heating, Bioacoustics, and Biomechanics, Ames Research Center, Moffett Field, Calif., January 25-27, 1966.

40. Levine, S. N. Advances in Biomedical Engineering and Medical Physics, Vol. 1, New York, N. Y.: Interscience Publishers, 1968.

41. Lincoln, R. S., and J. E. Mangelsdorf. An Integrated Approach to Evaluating the Performance Capabilities and Physiological State of Spacecraft Crews, Report No. 6-65-65-15, AD-616-316, Lockheed Missiles and Space Co., Sunnyvale, Calif., April 1965.

42. Lindsey, Jefferson F., and John C. Townsend. Biomedical Research and Computer Application in Manned Space Flight, NASA-SP-5078, NASA, Washington, D. C., 1971.

43. Lovelace Foundation for Medical Education and Research: Compendium of Human Responses to the Aerospace Environment, Vol. III, Sections 10-16, Albuquerque, N. Mex., November 1968.

44. Lunc, M. "Bioastronautics", Nineteenth International Astronautical Federation, Congress, Vol. 4, New York, N. Y., October 13-19, 1968.

45. Mandrovsky, Boris. Bioinstrumentation, Aerospace Technology Division, Library of Congress, Washington, D. C., 1968.

46. Martin Marietta Corporation: Skylab Program, Detail Design Summary for Operational Bio-Instrumentation System, Contract NAS8-24000, Amendment MSC-14S, Hardware Directive 6, February 22, 1971.

47. Meehan, J. P., and R. D. Rader, "Applications of Miniature Biotelemetry Systems to Space Medicine", Instrument Society of America, Pittsburgh, Pa., 1967, pp. 245-250.

48. Merrill, G. L., and J. B. Starr, Fluidic Temperature Control System for Liquid-Cooled Space Suits, NASA-CR-108330, NAS9-8249, Honeywell, Inc., Minneapolis, Minn., 1969.

49. Morehouse, L. E. Model of a System Utilizing Heat Rate to Monitor Man at Work in an Alien Environment, California University, Human Performance Lab., Los Angeles, Calif., 1969.

50. NASA: Apollo 11 Mission Report, NASA-SP-238, Manned Spacecraft Center Mission Evaluation Team, Houston, Tex., 1971.

51. NASA: Biomedical Research and Computer Application in Manned Space Flight, NASA-SP-5078, J. F. Lindsey and John C. Townsend (eds.)

52. NASA: Guidelines for EVA Development, NASA-TM-X-62444, Manned Spacecraft, Houston, Tex., 1967.

53. North American Rockwell Corp.: Extravehicular Engineering Activities (EVAA) Program Requirements Study. Appendix C - Scientific/Technical Experiments Baseline, Final Report, NAS8-18128, NASA-CR-95914, Downey, Calif., May 6, 1968.

54. Northrop Corp.: Biomedical Recording Systems, NAS9-7856, NASA-CR-101978, Van Nuys, Calif., August 1969.

55. Parin, V. "Biotelemetry Gives Medical Data on Space Fliers", Joint Publications Research Service, Washington, D. C., March 10, 1969.

56. Paul, A. P., and F. J. Wancho. "The Mission Control Center Biomedical Data Analysis and Display System", National Telemetering Conference, Houston, Tex., Lewis Winner, New York, N. Y., 1968, pp. 342-347.

57. Physiological and Performance Determinants in Manned Space Systems, Vol. 5 of Science and Technology Series, H. Jacobs (ed.) Western Regional Meeting of American Astronautical Society, no date.

58. Rasquin, J. R. Metabolism Monitor for Space Activity, U. S. Patent Application #SN-873792, NASA-CASE-MFS-20092, Marshall Space Flight Center, Huntsville, Ala., 1969.

59. Ratino, David A., Adolph R. Marko, and William C. Kaufman. Description and Operating Instructions for a 7-Channel Telemetry System for Physiological Temperatures and the Electrocardiogram, Report No. AMRL-TR-68-140, Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, October 1968.

60. Robertson, W. G., and E. C. Wortz. "The Effect of Lunar Gravity on Metabolic Rates", LS67-2174, NASA 6494, Aerospace Medicine, June 1967.

61. Roth, H. P. "Work and Thermal Loads on Men Working in Space Suits", N66-17395, A Collection of Papers on Spacesuits and Human Performance, Chrysler Corp., New Orleans, La., August 16, 1965.

62. Sanborn, W. G., and E. C. Wortz. "Metabolic Rates During Lunar Gravity Simulation", Aerospace Medicine, Vol. 38, No. 4, 1967.

63. Schaefer, H. "Radiation Monitoring on Project Mercury", Aerospace Medicine, Vol. 40, December 1969, pp. 1509-1516.

64. Seale, L. M. "EVA Space Missions - An Overview of the Requirements", National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

65. Shafer, W. A. "Telemetry on Man Without Attached Sensors", New York State Journal of Medicine, Vol. 67, November 1, 1967, pp. 2832-2837.

66. Simons, David G., and William C. Sparkman. The Anchor Button: An Attachment Technique for Biomedical Instrumentation Lead Wires, Report No. SAM-TR-65-64, School of Aerospace Medicine, Brooks AFB, Tex., September 1965.

67. Stolwijk, Jan A. Thermal Loads in Lunar Ambulation, John B. Price Foundation, Yale University, New Haven, Conn. 06519.

68. Stolwijk, Jan A., et al. "Physiological Factors Associated with Sweating During Exercise", Aerospace Medicine, October 1968.

69. Spady, Amos A., Jr., and W. D. Krasnow. Exploratory Study of Man's Self-Locomotion Capabilities with a Space Suit in Lunar Gravity, NASA-TN-D-2641, 1966.

70. Troutman, S. J., Jr., and P. Webb. Automatic Control of Water Cooled Suits from Differential Temperature Measurements, Final Report, NASA-CR-86244, NAS12-682, Webb Associates, Yellow Springs, Ohio, 1969.

71. Turnbow, F. J. Thermal Property Measurements of Manned Spacecraft Center Spacesuit Materials, Measurements Report, NASA-CR-92198, TRW-68-3346, TRW Systems, Redondo Beach, Calif., May 1968.

72. University of Texas Graduate School of Biomedical Sciences: Development of Computer Technology for Medical Data Analysis to be Applied to Apollo and Follow-on Space Missions, Final Report, NAS9-7029, NASA-CR-92377, August 1968.

73. Van Schaik, Peter N., and Leonard M. Seale. Space Extravehicular Operations: A Review of the Requirements and Alternate System Approaches, Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio, October 1966.

74. Weibel. Morphometry of the Human Lung, New York, N. Y.: Academic Press, 1963, p. 111.

75. Wortz, E. C. "Metabolic Demand During Man's Lunar Activity in Space Suits", NASA Marshall Space Flight Center Fifth Annual Meeting, Working Group on Extraterrestrial Resources, March 3, 1967, pp. 219-222.

76. Wortz, E. C., et al. "Study of Heat Balance in Full Pressure Suits", Aerospace Medicine, February 1967.

77. Wortz, E. C., and E. J. Prescott. The Effects of Subgravity Traction Simulation on the Energy Cost of Walking", Aerospace Medicine, Vol. 37, No. 12, 1966.

BIBLIOGRAPHY OF SPACE TOOLS

SPACE TOOLS

1. AAI, Inc.: Final Report for Cutting Tool for Use in Space, July 1967.

2. Adams, C. R. "Some Human Factors Considerations for an Orbital Maintenance and Materials Transfer Shuttle", Aerospace Medical Association, Thirty-fifth Annual Scientific Meeting, Bal Harbour, Fla., Douglas Aircraft Co., Inc., May 1964, pp. 1-3.

3. Adams, C. R., and G. Hanff. "Some Human Factors Considerations for Orbital Maintenance and Materials Transfer", Aerospace Medicine, Vol. 36, March 1965, pp. 223-230.

4. Aerojet General Corp.: Operating and Maintenance Instruction for Tool, Bolt Installation and Removal, An-1968, August 1969.

5. Aerojet General Corp.: Bolt Installation and Removal Tool, NAS8-30026, Report No. 61315, September 1969.

6. Aircraft Armaments, Inc.: Cutting Tool for Use in Space, Final Report, NAS8-20680, NASA-CR-88860, Cockeysville, Md., July 1967.

7. Air Force Propulsion Lab.: Second National Conference on Space Maintenance and Extravehicular Activities, August 6-8, 1968, Las Vegas, Nev., AF-8170, February 1969.

8. "Aldrin Shows Man Can Work in Space", Aviation Week and Space Technology, November 21, 1966, pp. 30.

9. Annis, J. F., and P. Webb. The Principle of the Space Activity Suit, NAS1-6872, NASA-CR-973, Webb Associates, Yellow Springs, Ohio, December 12, 1967.

10. Asbury, E. J. Open End Flat Ratchet Wrench, ORGDP K-D-2189, July 18, 1969.

11. Beasley, G. P., and W. W. Hankins. "Development of Electroadhesive Devices for Zero-g Intra/Extravehicular Activities", AIAA/ASMA Weightlessness and Artificial Gravity Meeting, AIAA Paper Number 71-853, August 9-11, 1971.

12. Beck, R. P. An Engineering Study of Onboard Checkout Techniques, Final Report, Task 3, NAS9-11189, IBM, Huntsville, Alabama, March 1971.

13. Belless, R. M., Jr. "Portable Astronauts Test Kit", NAS8-24296, Martin Marietta Corporation, Denver Division, May 1970.

14. Belless, R. M., Jr., and L. R. Anderson. "Needed: Space Maintenance Tools", Reliability and Maintainability Conference, Detroit, Mich., July 1970.

15. Blaise, H. T. Contract Acceptance Bench Testing Bolt Installation and Removal Tool (BIRT), MSFC, Huntsville, Ala., 1969.

16. Bleckschmidt, C., and C. Clark. Design and Tests of the Martin Powercrane Handheld Extravehicular Propulsion Unit, Third American Institute of Aeronautics and Astronautics and NASA Manned Space Flight Meeting, Houston, Tex., November 4-6, 1964.

17. Boring, K. L., T. M. Dickson, W. McMurray, L. H. Stauffer, E. F. Travis, and C. Zubal. Plasma Electron Beam Welder for Space Vehicles, General Electric Research and Development Center, August 1968.

18. Bradley, W. E. "Telfactor Control of Space Operations", Astronautics and Aeronautics, Vol. 5, May 5, 1967, pp. 32-38.

19. Brazell, Robert R., and W. G. Thompson. Assembly and Maintenance of Lightweight Metallic Structures in Space, Final Report, February 1967 - July 1968, Contract No. F33615-67-C-1302, General Dynamics/Convair, San Diego, Calif., March 1969.

20. Brecker, L. "Working in Space: Are We Ready?" Space Aeronautics Magazine, October 1966.

21. Burnett, J. R. Development of the Swing-out Module -- An Aid to Spacecraft Subsystem Maintenance, Report No. GDC-ERR-AN-1118, General Dynamics/Convair, San Diego, Calif., October 1967.

22. Cains, F. L. The Feasibility of Manned Orbital Maintenance, Douglas Aircraft Co., Inc., Santa Monica, Calif., January 31, 1962.

23. Carpenter, R. B., Jr. "How Big is the Space Flight Maintenance Problem/ Question?" First National Conference on Space Maintenance and Extravehicular Activities, March 1-3, 1966, Orlando, Fla., pp. 6.1.1-6.1.12.

24. Cohen, H. "Long Duration Space Missions Through Use of In-Flight Maintenance", Sixth Annual Reliability and Maintainability Conference, July 17-19, 1967, Cocoa Beach, Fla., 1967, pp. 104-112.

25. Coleman, E. R. Evaluation of S-IVB Window Emplacement Tool Kit, Hayes International Corp., January 29, 1969.

26. Cooley, W. C. Investigation of Precision Control and Orbit Maintenance Systems for Rotating Space Stations, Bimonthly Progress Report, Exotech, Inc., Alexandria, Va., January 31, 1963.

27. Cording, Carl R. "Extravehicular Maintenance and Techniques:, AIAA Second Manned Space Flight Meeting, General Electric Co., Valley Forge, Pa., 1963, pp. 86-91.

28. Costick, J. R., III. "The Necessity for Development and Use of Fastening Devices with Special Characteristics for Space Use", First National Conference on Space Maintenance and Extravehicular Activities, March 1-3, 1966, Orlando, Fla., 1966, pp. 2.7.1-2.7.8.

29. Crouch, D. S. Design Study for Lunar Exploration Hand Tools, Martin Company, Manned Spacecraft Center, Houston, Tex., December 1965.

30. Crouch, D. S. Familiarization Support Manual, Apollo Lunar Surface Drill (ALSD), ER 14756, Martin Marietta Corp., July 15, 1968.

31. Crouch, D. S. Final Report for Apollo Lunar Surface Drill (ALSD), ER 14778, Martin Marietta Corp., Manned Spacecraft Center, Houston, Tex., November 1, 1968.

32. Crouch, D. S. Second Quarterly Report, Design Study for Lunar Exploration Tools. NASA-CR-65693, Martin Co., Baltimore, Md., April 1965.

33. Daisey, Floyd K. Experiment D-16: Space Power Tool, Program 631A, Vol. XIII, Summary Report, Contract No. AF 33(615) - 2121 and AF 33 (615) - 3562, August 1964 - February 1967, Martin Co., Baltimore, Md., June 1967.

34. Daisey, Floyd K. Space Power Tool, Tech. Report No. RTD-TDR-63-4227, Martin Co., Baltimore, Md., April 1964.

35. Daisey, Floyd K. Space Power Tool System for Experimentation on Gemini, Final Report, Report No. ER-14114, Contract No. AF 33(615) - 2121, August 1964 - August 1965, Martin Co., Advanced Logistics Dept., Baltimore, Md., August 1966.

36. Demarino, D. Extravehicular Space Maintenance, AD 836 374L, Bethpage, N.Y., December 1966.

37. DesCamp, Victor A., Michael W. Hussey, Joseph A. Lenda, and Billy B. Taylor. Modification of an Astronaut's Mockup Tool Kit, Final Report, NAS8-26448, NASA-CR-103135, Martin Marietta Corp., Denver, Colo., April 1971.

38. Economos, A. M. The Douglas Space Station Maintenance Simulation, Manned Space Reliability Symposium, Anaheim, Calif., June 9, 1964.

39. Edmund, I. Space Power Tool, Marshall Space Flight Center, Huntsville, Ala., June 18, 1969.

40. "Electron Beam Welding in Space", The Engineer, Vol. 225, June 28, 1968, pp. 1024-1025.

41. Elkins, W. "Hard Shell Suit Performance as It Relates to Space Maintenance and Other Extravehicular Activities", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 5.1.1-5.1.6.

42. Fagan, R. L., and M. A. Wilson. Maintainability in Space - A Survey, AIAA Tech. Information Service A67-30445, General Electric Co., December 20, 1966.

43. Firstman, S. F. "In Space Support", Space/Aeronautics, Vol. 42, 1964, pp. 227-229.

44. Forbes, F. A., C. B. May, and P. N. Van Schaik. Space Maintenance Hangar Concepts, Air Force Systems Command, Wright-Patterson AFB, Ohio, March 1964.

45. Gangwer, K. E. "Computer Produced Maintenance Documentation", Second Annual Convention, Society of Logistics Engineers, September 19-20, 1967, Washington, D.C., 1967, pp. 226-244.

46. Geller, R. E., and W. R. Pierson. "Orbital Maintenance", Journal of Spacecraft and Rockets, Vol. 3, June 1966, pp. 941-942.

47. General Dynamics: "Research and Applications Module (RAM)", Phase B Study, NAS8-27539, Convair Aerospace Div., 1971.

48. General Electric Co. "A Study of Teleoperator Technology Development and Experiment Programs for Manned Space Flight Applications", NAS9-11067, Space Systems Organization, January 1971.

49. Glazer, D. L., and B. A. Thill, Jr. "Operator/Tool Interface Problem Areas for Space Maintenance", NA89-3161, First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 5.6.1-5.6.10.

50. Grumman Aircraft Engineering Corp.: Satellites and Vehicles Assembled in Space, AD 838 528L, Bethpage, N.Y., April 1968.

51. Hamilton, A. L., and A. E. Holmes. "A Space Tool Kit Development Program", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., 1966, pp. 2.1.1-2.1.15.

52. Hanny, J. E., G. H. Peters, and R. J. Shafer. "Extravehicular Capsular Adhesive Systems", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 2.2.1-2.2.11.

53. Hanny, J., G. Peters, and J. Whitaker. Extravehicular Space Adhesive System, National Cash Register Co., Dayton, Ohio, August 1966.

54. Havener, P. W., L. B. Johnson, S. J. Raff, and E. F. Wilcomb. Research Program on Tools for Future Manned Space Flights, Phase I, Final Report, Raff Analytic Study Associates, Inc., Silver Springs, Md., March 27, 1967.

55. Hibben, R. D. "U.S.A.F. Studying Space Tool Development", Aviation Week and Space Technology, September 13, 1965, pp. 50-79.

56. Holmes, A. E. Space Tool Kit - Survey, Development and Evaluation Program, Final Report, NAS9-3161, NASA-CR-65267, Martin Co., Baltimore, Md., 1964.

57. Holmes, A. E., and C. B. May. An Evaluation of Man's Capability to Perform Support Functions in Space, Seventeenth International Astronautical Congress, October 10-15, 1966, Madrid, Spain, 1967.

58. Iribe, P., and J. A. Lieske. Study of Extravehicular Protection and Operations, NASA-CR-773, NASA Order R-21-009-00, Johns Hopkins University, Baltimore, Md., June 1967.

59. Iribe, P., and J. A. Lieske. "Environmental and Mobility Constraints on the Configuration of a Nonanthropomorphic Space Suit", N68-18729, First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

60. Jeppesen, M. L., B. W. Reynolds, N. C. Costakos, N. E. Houtz, and E. Rottmayer. Study on Methods of Structurally Evaluating Expandable Structures Having Potential Space Applications, Quarterly Report, Contract No. NASW-471, Goodyear Aircraft Corp., Akron, Ohio, November 10, 1962.

61. Johnson, J. H. Site Bench Maintenance Test Set, First AIAA Annual Meeting, Washington, D.C., June 29 - July 2, 1964.

62. Johnson, L. B. A Review of Maintenance Performance Decrements Resulting from Weightlessness and Pressure Suit Conditions, Phase I Report, Report No. 66-23, Raff Analytic Study Associates, Inc., February 27, 1967.

63. Johnson, L. B. Experimental and Engineering Research Studies on Tools for Extravehicular Maintenance in Space, Second National Conference on Space Maintenance and Extravehicular Activities, August 6-8, 1968.

64. Johnson, L. B., and P. W. Havener. Experimental Research Studies on Tools for Extravehicular Maintenance in Space, Report 67-9, NASA-CR-91052, Raff Analytic Study Associates, August 31, 1967.

65. Johnson, L. B., P. W. Havener, S. J. Raff, and E. R. Wilcomb. Future Manned Space Flights, RASA 66-247, NASA-CR-85556, Raff Analytic Study Associates, Inc., March 27, 1969.

66. Johnson, L. B., E. Sander, and S. Lebow. NASA List of Potential Space Tools and Equipment, NAS2-5073, NASA-CR-1760, Raff Analytic Study Associates, Inc., Silver Springs, Md., May 1971.

67. Jones, R. A., and G. H. Sievert. Exothermic Space Bonding System, AFAPL-TR-66-63, Air Force Aero Propulsion Lab., Research and Technology Division, Wright-Patterson AFB, Ohio, August 1966.

68. Jones, R. A., and G. H. Sievert. Exothermic Space Bonding System, Final Technical Report, Whittaker Corp., June 1, 1965 - February 28, 1966, San Diego, Calif., 1967.

69. Karmiol, P., Robert Knaff, and John S. Youtcheff. "Space Reliability Through Man-Equipment Synthesis", Twelfth International Astronautical Congress, Vol. 42, Washington, D.C., October 1-7, 1961, pp. 564-579.

70. Keating, M. R. Feasibility Study of an Expandable Space Maintenance Hangar, M. S. Thesis, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, March 1966.

71. Kohn, Marvin L. Materials Joining Tool, Final Report, May 1967 - April 1968, Hamilton Standard, Windsor Locks, Conn., September 1968.

72. Kohn, M., and C. W. Silha. Cold Cathode Welding for Space Applications, Second National Conference on Space Maintenance and Extravehicular Activities, August 6-8, 1968.

73. Kubokawa, C. C. Space Tool State-of-the-Art and Considerations for Future Space Tool Equipment Design, Joint National Meeting, American Astronautical Society - Operations Research Society, Denver, Colo., June 17-20, 1969.

74. Lawrence, G. S., and F. R. Schollhammer. Hand-Held Electron Beam Gun and External Power Supply, Final Report, Hamilton Standard, Windsor Locks, Conn., EBR 199, October 1966.

75. Manned Spacecraft Center: Gemini Summary Conference, NASA SP-138, Houston, Texas, Febraury 1-2, 1967.

76. Manned Spacecraft Center: Summary of Gemini EVA, R. M. Machell (ed.), NASA SP-149, Houston, Texas, 1967.

77. Marshall Space Flight Center: "LST Maintenance Analysis", MSFC Program Development, Huntsville, Ala., December 1971.

78. Marshall Space Flight Center: Space Tool Development, Vol. 1 - State-of-the-Art Survey, NASA TMX-53725, Huntsville, Alabama., August 15, 1968.

79. Martin Co.: First National Conference on Space Maintenance and Extra-vehicular Activities, Orlando, Fla., March 1-3, 1966.

80. Martin Marietta Corp.: Apollo Surface Drill (ALSD), Phase C Final Report/Phase D Technical Proposal, ER14349P, August 18, 1966.

81. Martin Marietta Corp.: Skylab Inflight Maintenance (IFM) Integration Report, NAS8-2400, Martin Marietta, Denver Division, ED-2002, 1969.

82. Martin Marietta Corp.: Skylab Operations Handbook, NAS8-2400, Houston, Texas, July 19, 1971.

83. Martin Marietta Corp.: Special Tool Kit Aids Heavily Garmented Workers, NASA Tech. Brief 66-10403, September 1966.

84. May, C. B. Maintenance in a Weightless Environment, AIAA Tech. Information Service, A65-22250, AFAPL Wright-Patterson Air Force Base, Ohio, April 1965.

85. May, C. B. "Maintenance Technology for Space Systems", N66-27274, Aerospace Expandable Structures, 1966, pp. 179-197.

86. May, C. B., J. N. Schofield, and L. A. Vorst. "AF-Gemini Space Maintenance Experiment and Simulation", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 4.1.1-4.1.18.

87. McKnowen, P. "Computer Simulator of Maintenance Tradeoffs", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 6.2.1-6.2.20.

88. Melpar, Inc.: Pilot Model Leak Detector for Space Environment, NASA MSFC Contract No. NAS8-20621, March 1969.

89. Melpar, Inc.: Qualification Test Report of Pilot Model Leak Detector for Space Environment, Contract No. NAS8-20621, March 1969.

90. Miller, E. A., G. Miller, and D. G. Norman. Human Engineering Studies for Maintenance and Repair in Zero Gravity, American Institute of Aeronautics and Astronautics, Space Program Issues of the 70's Meeting, Seattle, Washington, August 28-30, 1967.

91. Mueller, Donald D., Jerome S. Seeman, and Francis H. Smith. A Technique to Investigate Space Maintenance Tasks, Report No. AMRL-TR-66-32, Aerospace Medical Research Lab., Wright-Patterson AFB, Ohio, April 1966.

92. Mueller, D. D., J. S. Seeman, and F. H. Smith. Preliminary Investigation of Space Maintenance, NASA-TM-X-53246, Marshall Space Flight Center, Huntsville, Alabama, June 15, 1966.

93. NASA: Astronaut's Tool for Withdrawing/Replacing Computer Cards, NASA Technical Brief 69-10183, July 1969.

94. NASA: Reference Earth Orbital Research and Applications Investigations (Blue Book), Vol. 1, NHB 7150.1, January 15, 1971.

95. North American Aviation, Inc.: Apollo In-Flight Maintenance Concept, NAS9-150, April 5, 1964.

96. Pecorado, F. R. Operation and Maintenance Instructions, MSFC, Contract No. NAS8-20796, December 1967.

97. Peterson, C. R., and R. Rochon. "Evaluation of Adhesive System for Anchoring Astronauts to a Worksite in Space", AFAPL-TR-65-10, Aero-Space Expandable Structures in Maintenance Support Devices, Vol. II, Archer Daniels Midland Co., July 1965.

98. Pillotson, R. W. Design for In-Flight Maintenance for Manned Space Missions, Society of Automotive Engineers, National Aeronautics and Space Engineering and Manufacturing Meeting, Honeywell Inc., Los Angeles, Calif., October 5-9, 1964.

99. Rader, P. J. Variable Flexibility Tether Systems, Final Report, General Electric Co., Philadelphia, Pa., May 1967 - February 1968.

100. Saenger, E. L., and C. D. Pegden. "A Study on Teleoperator Systems Performance Requirements", Mission Analysis Briefing, NAS8-27013, URS/Matrix Co., Huntsville, Alabama, December 1971.

101. Saenger, E. L. "Manual and Automated Extravehicular Cargo Handling Systems - State-of-the-Art", NASA/McDonnell Douglas Space Cargo Handling Conference, August 1970.

102. Saenger, E. L., T. B. Malone, and K. M. Mallory. "Selection of Systems to Perform Extravehicular Activities (Man and Manipulator)", Vol. 2, Final Report, NAS8-24384, Matrix Research, Huntsville, Alabama, April 1969.

103. Schollhammer, F. R. "Electron Beam Welding for In-Space Assembly and Maintenance", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 2.6.1-2.6.26.

104. Schollhammer, F. R. Electron Beam Welding in Variable Environments, Hamilton Standard, United Aircraft Corp., October 14, 1963, - January 14, 1964.

105. Schwinghamer, R. J. "Tool Experiments for Assembly, Maintenance and Repair in Space", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966, pp. 4.6.1-4.6.31.

106. Seale, L. M. "EVA Space Missions - An Overview of the Requirements", First National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1-3, 1966.

107. Seale, L. M. Study of Space Maintenance Techniques. Bell Aero Systems Co., Aero Space Rockets Division, May 1963.

108. "Space Wrench Won't Rotate the Astronaut", Machine Design, August 1965.

109. "Tools for Space", Machine Design, November 22, 1962, pp. 134-138.

110. Van Schaik, Peter N. An Assessment of the Practicality of Orbital Maintenance, Report No. AFAPL-Conf-68-3, Air Force Aero Propulsion Lab, Wright-Patterson AFB, Ohio, August 1967.

111. Van Schaik, Peter. Latest Developments for EVA Space Operations, AFAPL, October, 1968.

112. Van Schaik, P. N. Multipurpose Propulsion Unit for Space Maintenance, Paper No. 65-258, Manned Space Flight Conference, Dayton, Ohio, April 21-23, 1965.

113. "What Will the Maintenance Tools of Astronaut Mechanics Be Like?" Naukai: Zhizn (Russian), Translated by U.S. Air Force Systems Command, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, November 8, 1964, pp. 124-125.

114. Wilson, W. A. Multipurpose Space Tool Evaluation, NASA, MSFC, MDM-5-68, April 1, 1968.

115. Wuenscher, H. F. Low and Zero-g Manufacturing in Orbit, Marshall Space Flight Center, Huntsville, Ala. October 23-27, 1967.

116. Yost, V. H. The Martin/Black and Decker Space Tool System Evaluation, Final Report, NASA-TM-X-53605, Manufacturing Research and Technology Division, Manufacturing Engineering Lab., May 1967.

117. Yost, V. H., and W. S. McBride. Multipurpose Tool Concept Interim Report, Marshall Space Flight Center, Huntsville, Ala., MDM-1-67, February 1, 1967.

APPENDICES

APPENDICES TABLE OF CONTENTS

APPENDICES LIST OF FIGURES

APPENDICES LIST OF FIGURES (Cont'd.)

APPENDICES LIST OF FIGURES (Cont'd.)

APPENDICES LIST OF TABLES

APPENDIX A

A BRIEF HISTORY OF ADVANCED PRESSURE SUIT DEVELOPMENT

APPENDIX A

A BRIEF HISTORY OF ADVANCED PRESSURE SUIT DEVELOPMENT

Advanced pressure suits are defined in this document as those suits having the following characteristics in common:

- They were developed with operating pressures of from 5 psig up to 14.7 psig. (Current operational pressure suits operate in the 3 to 3.7 psig range.)
- They exhibit "passively" stable joints (i.e., the suit or joint elements of the suit have no neutral position and are stable throughout their joint ranges.)
- They exhibit very low operational torques (in the vicinity of 10 to 20 times less torque than the operational suits).

1957 - Litton "Mark I" Suit (Figure A-1)

The first pressure suit, developed to operate at normal operating pressures of 5 psi was the Litton Mark I Hard Suit, which was evaluated in 1957 in the Litton Space Chamber.

In this suit, a series of cardonic elements combined to provide two-axis arm mobility. The fabric sections of the arm were controlled through the use of hat-box aluminum sections. The suit presented the first use of the rolling convolute concept common to all the Litton-developed 5 psi suits and the 14.7 psi Lunar Receiving Lab (LRL) arm. These LRL arms were attached to an aluminum upper torso, presenting an appearance very much like the tin man in the Wizard of Oz. Only the arms of this suit represented advanced technology. The lower torso was fabricated by Arrowhead Rubber Company and was of conventional construction.

1963 - RX-1 (Figures A-1 and A-2)

The first contract awarded to Litton by NASA for investigation of the rigid articulated suit was initiated in 1963. The guidelines for suit development specified a 5 psig operational pressure. This suit further developed the rolling convolute concept and initiated the design feature of having the hat-box sections stackable. The compactness of this joint system, combined with the use of sealed rotary bearings, allowed considerably more rigidizing of the suit with only a very small amount of the arm required to get 120° of elbow flexual range. The suit also introduced a 2-bearing shoulder joint system which has the rolling convolute section sandwiched between two large 12-inch shoulder bearings. The RX-1 success led to a follow-on effort in 1964 for the development of the RX-2 suit.

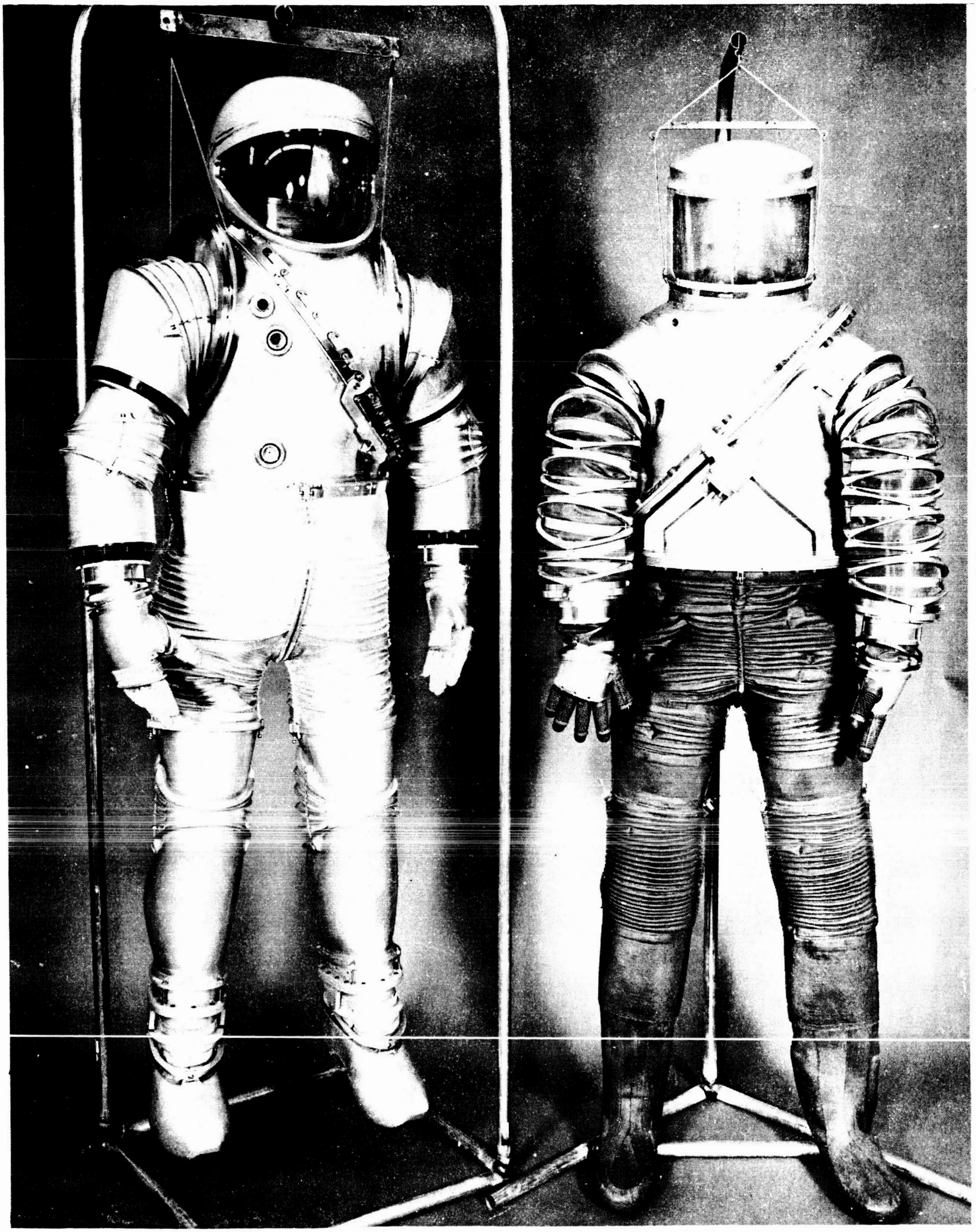


FIGURE A-1: RX-1 and Mark I Constant Volume Suits

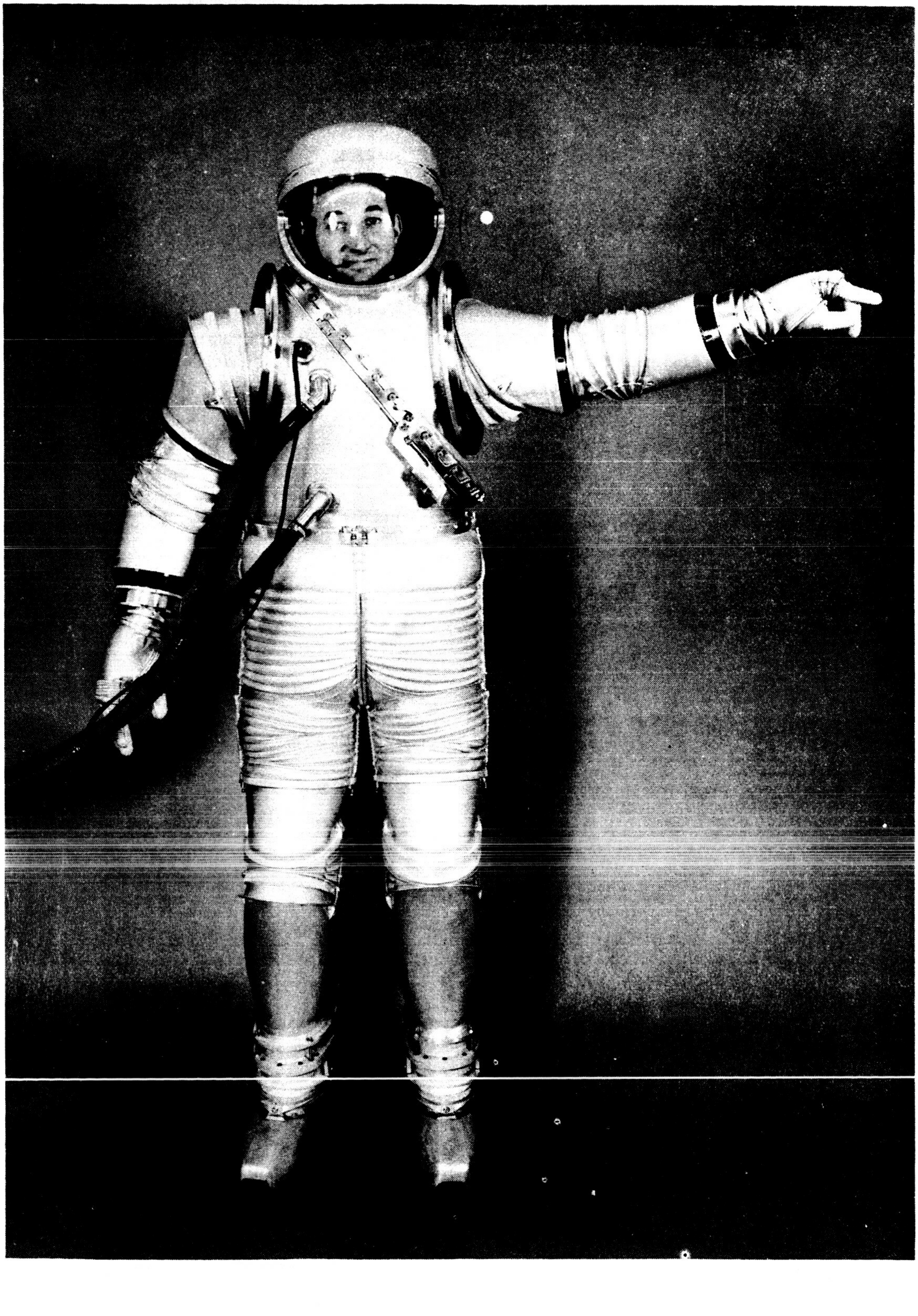


FIGURE A-2: RX-1 Suit

1964 - RX-2

This suit was identical to the RX-1, except that it introduced a hip joint into the system and totally eliminated any "soft" suit sections.

1964 - RX-2A (Figure A-3)

An important step in the development of the rigid articulated suit was the RX-2A, a suit which used the sandwich structure that became the basis of further development of the RX-3, RX-4, and RX-5 suits as well as the Lunar Receiving Laboratory arms. The inner shell of the sandwich structure was a formed aluminum skin. The sandwich material was fiberglass honeycomb, and the outer shell was a fiberglass/epoxy shell. The RX-2A introduced a 2-planar torso closure proceding horizontally under the arms and vertically across the back of the suit. A two-axis armored convolute concept, used from that point on in all the RX suits, was introduced; this concept provided two-axis mobility for the waist as well as the shoulder.

1965 - RX-3 (Figure A-4)

The RX-3 suit was a more operationally configured suit, having an improved shoulder joint, torso closure, and a weight reduction of some 20 pounds. The RX-3 weighed 63 pounds and was the first suit designed to use a modular sizing system of replaceable multiple sized shell sections. Large shoulder bearings were eliminated from the RX-3 by using a two-bearing "stovepipe" section immediately below the two-axis armored convolute shoulder joint.

1966 - RX-4

The RX-4 was similar to the RX-3 suit, with the exception of the introduction of a thermal outer garment.

1967 - AX-1 (Figure A-5)

The AX-1 hard suit, developed at the Ames Research Center in 1967, introduced the multiple bearing concepts. The suit was a marked departure from previous hard suits because of its reliance on multiple bearing joints at the shoulder, elbow, waist, ankle, knee and hip. Metal bellows were used at the hip and waist to provide increased mobility.

1967 - LRL Arms

The first suit components fabricated to operate at 14.7 psig were adaptations of the RX-3 arms. These arms were used in the Lunar Receiving Laboratory for initial studies on Lunar Samples which were accomplished in the LRL vacuum chamber. The ability to use these components at 14.7 psia greatly simplified the laboratory by eliminating air locks, subchambers, and medical monitors.

1968 - AX-2 (Figure A-6)

The AX-2 suit, also developed at the Ames Research Center, was a more sophisticated suit based on AX-1 technology. It introduced an angled rotary

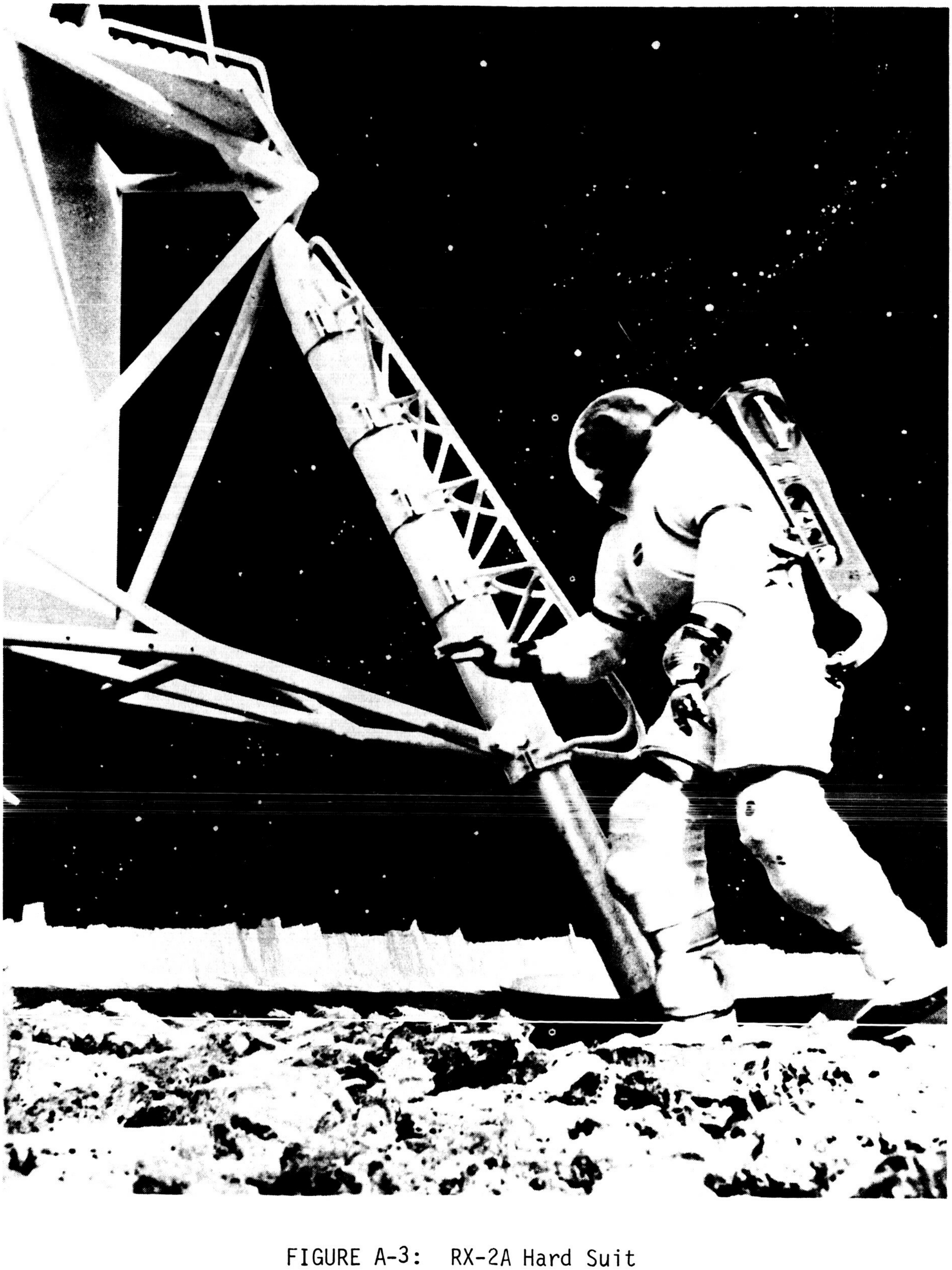


FIGURE A-3: RX-2A Hard Suit

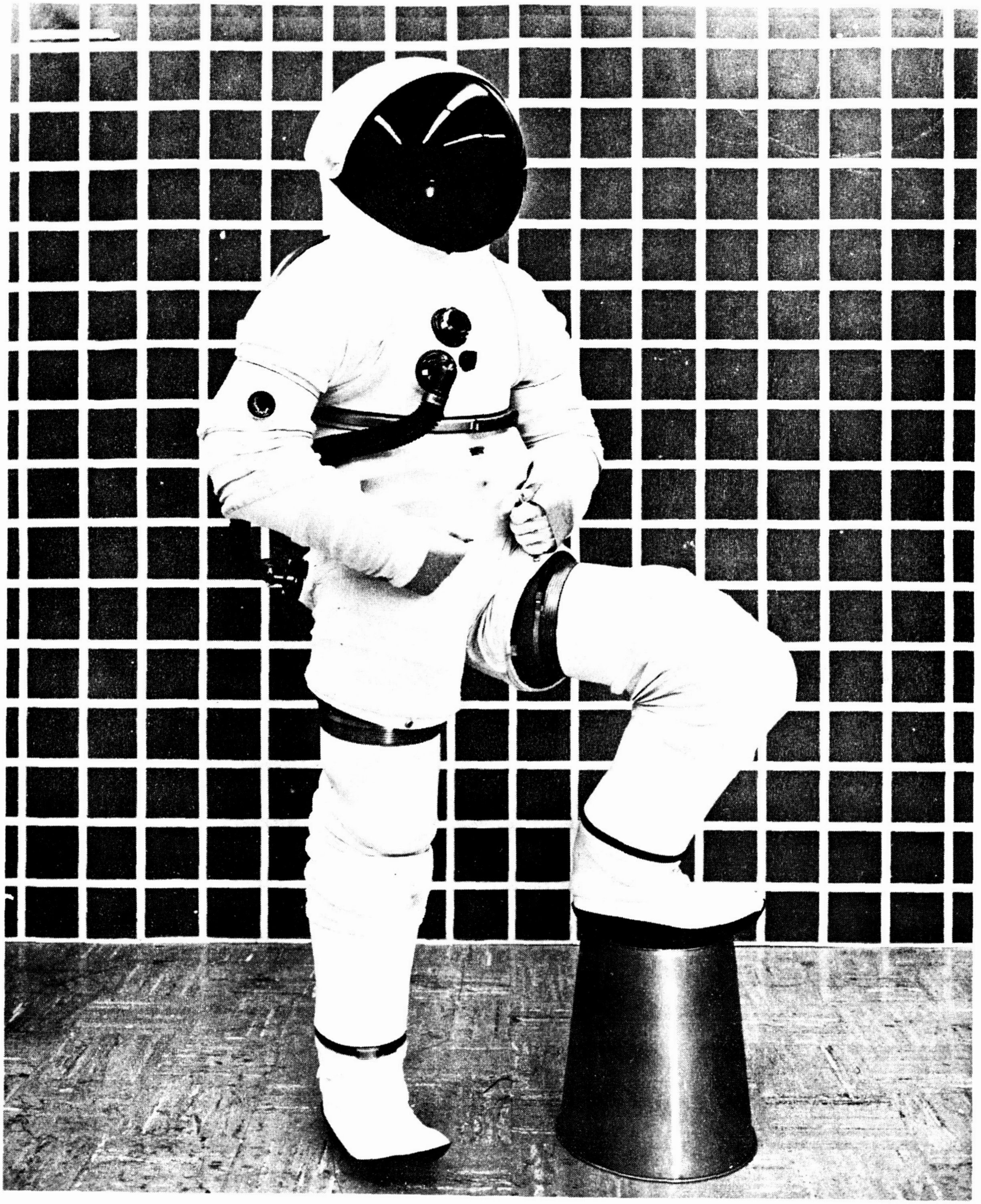


FIGURE A-4: RX-3 Hard Suit

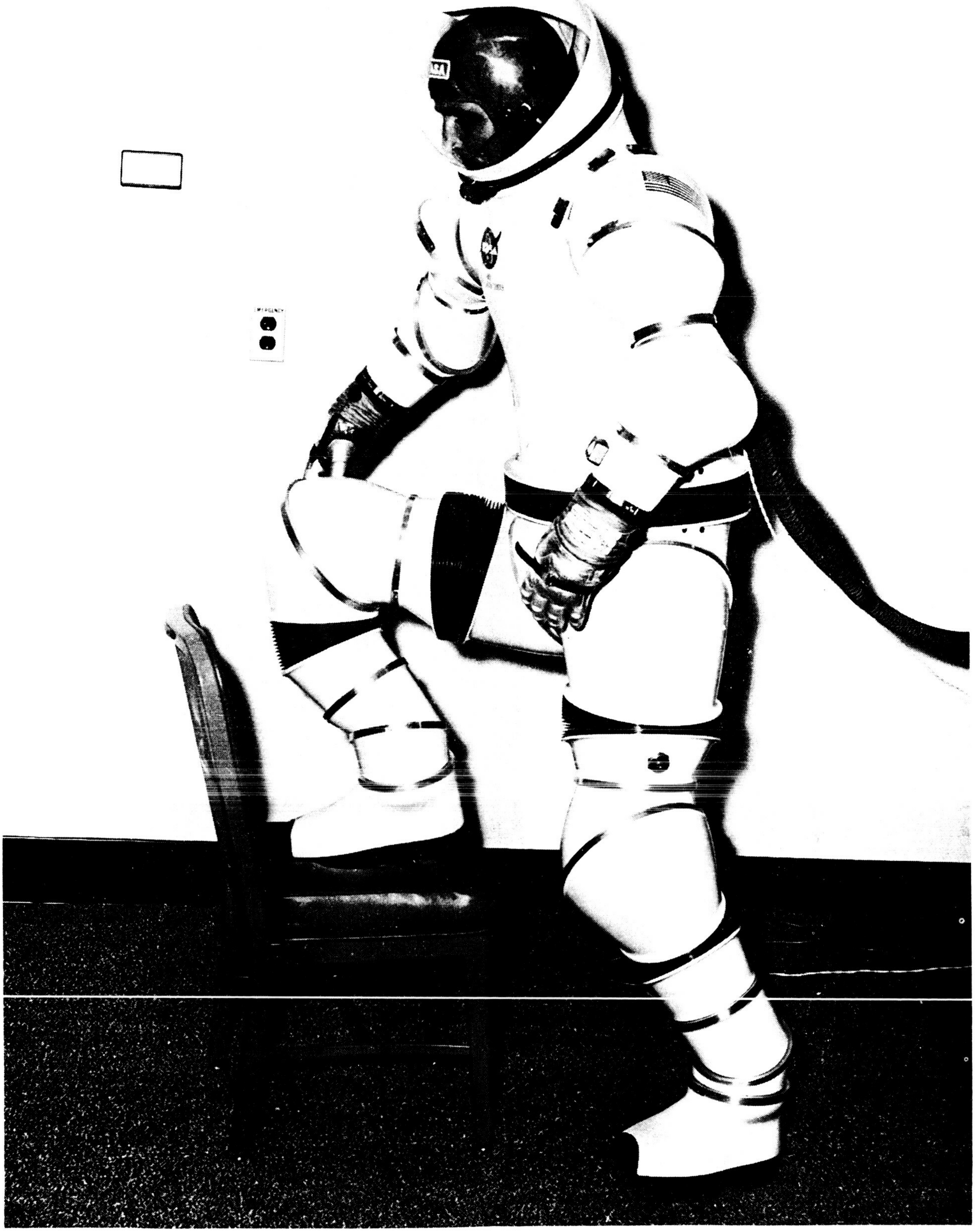


FIGURE A-5: Ames Research Suit AX-1

FIGURE A-6: Ames Research Suit AX-2

bearing in conjunction with a single axis metal bellows to provide two-axis waist mobility.

The impact of the Ames Research Center's work can be seen in the later developments of both the Litton Hard Suit (RX-5) and the AES suits developed in 1968-1969.

1968 - RX-5

The last version of the RX suit series to be developed was the RX-5. It combined the technologies of both hard suit systems, using a multiple bearing hip joint similar to that used in the AX-2 suit. A simple planar torso closure replaced the two planar units used in the RX-2, -3 and -4 suits. The waist joint was a single axis rolling convolute joint.

1968 - Advanced Soft Suits (Figure A-7)

Both Litton Industries and the AiResearch Corporation delivered soft or semisoft suits having mobility characteristics heretofore seen only in "hard" suits.

The Litton suit used a multiple bearing shoulder joint and hip joint as well as an angled rotary bearing/torso closure borrowed from the Ames AX-2 Hard Suit. The AiResearch Suit introduced a new convoluted technique which provided constant volume characteristics in a simple fabric joint. These convolutes were combined with the Ames multiple bearing techniques for the shoulders and hips and were used independently for the elbow, knee, and ankle and combined in series to provide two-axis mobility to the waist.

1969 - AES Suits (Figure A-8)

Two development efforts, conducted in parallel by Litton and AiResearch, led to the delivery of controlled suits aimed at prequalification testing of Advanced Lunar Suits.

The AiResearch AES suit utilized a five bearing shoulder joint developed in cooperation with Ames. It also featured design refinements which allowed it to be stowed in the existing Apollo Suit Stowage bag. (See Figures A-9 and A-10).

The Litton AES suit used a single axis rolling convolute system sandwiched between two bearings; otherwise the techniques used in this advanced soft suit (1968) remained unchanged.

Present

The NASA Manned Spaceflight Center (MSC) is currently involved in developing an advanced pressure suit to operate in an 8.0 to 14.7 psi range for future missions. Data concerning this suit and the status of its development were not available for inclusion in this document.

FIGURE A-7: EX-1A Advanced Soft Suit

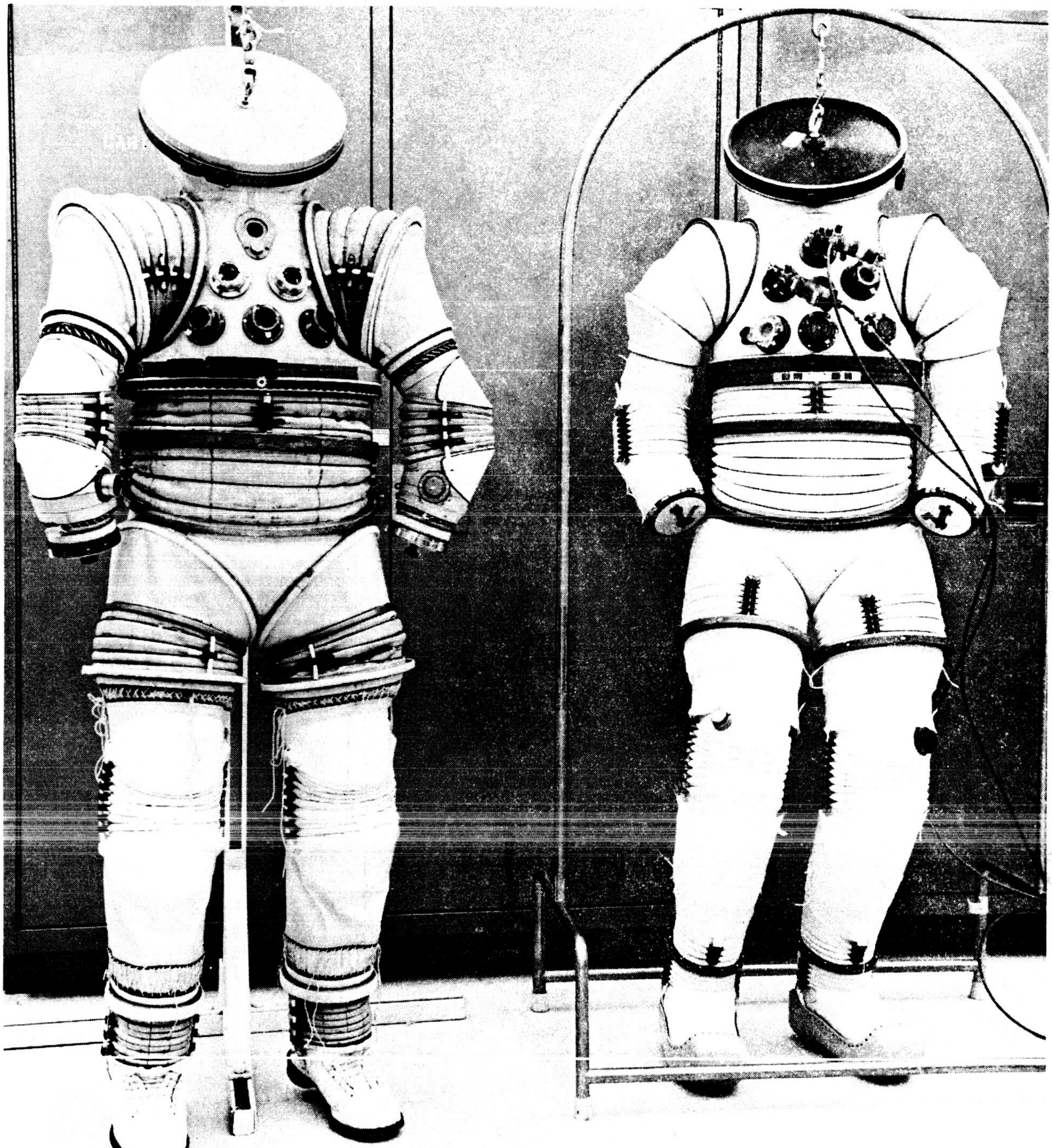


FIGURE A-8: EX-1A and AES Suits

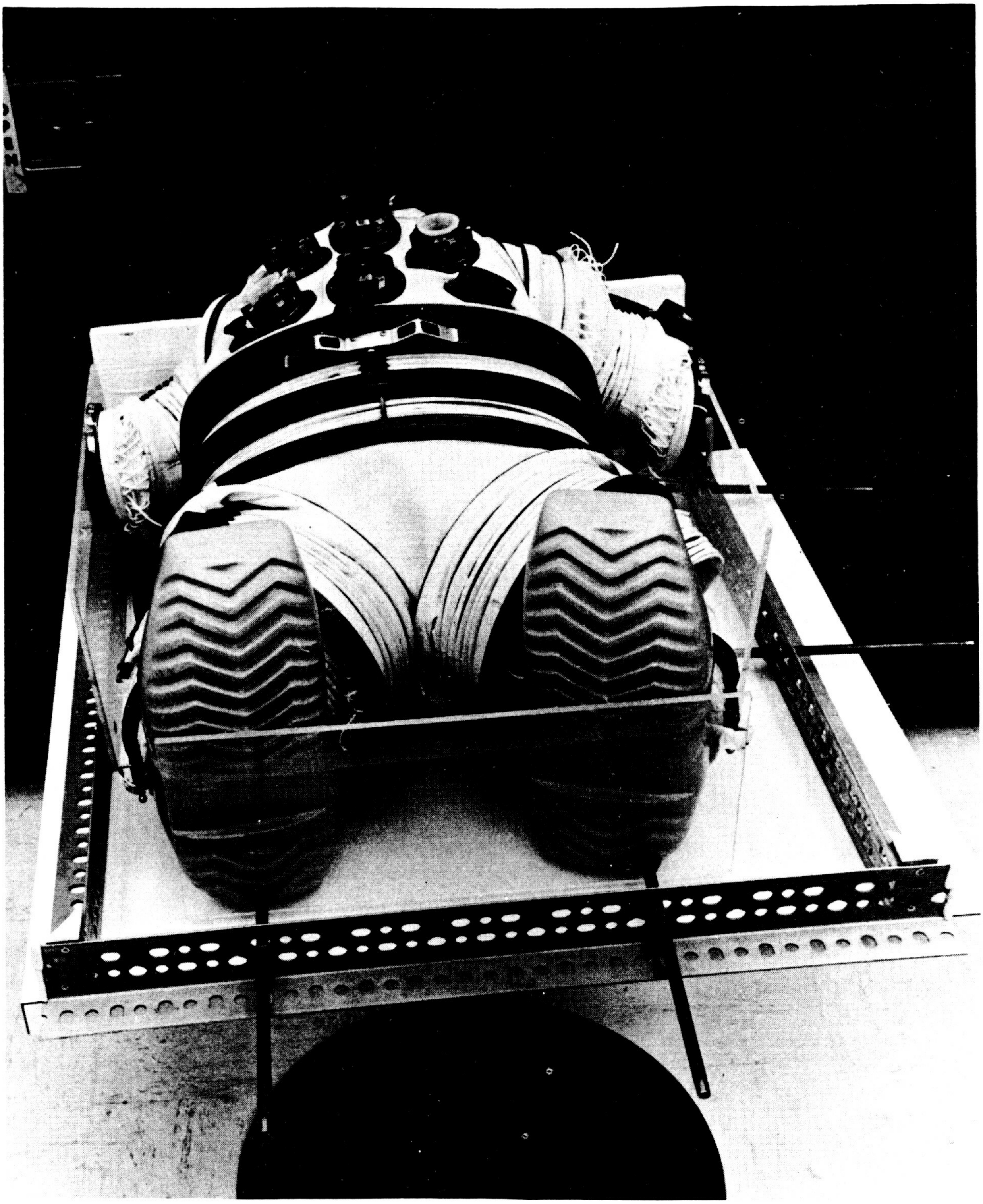


FIGURE A-9: Front View of Suit in Stowage Configuration

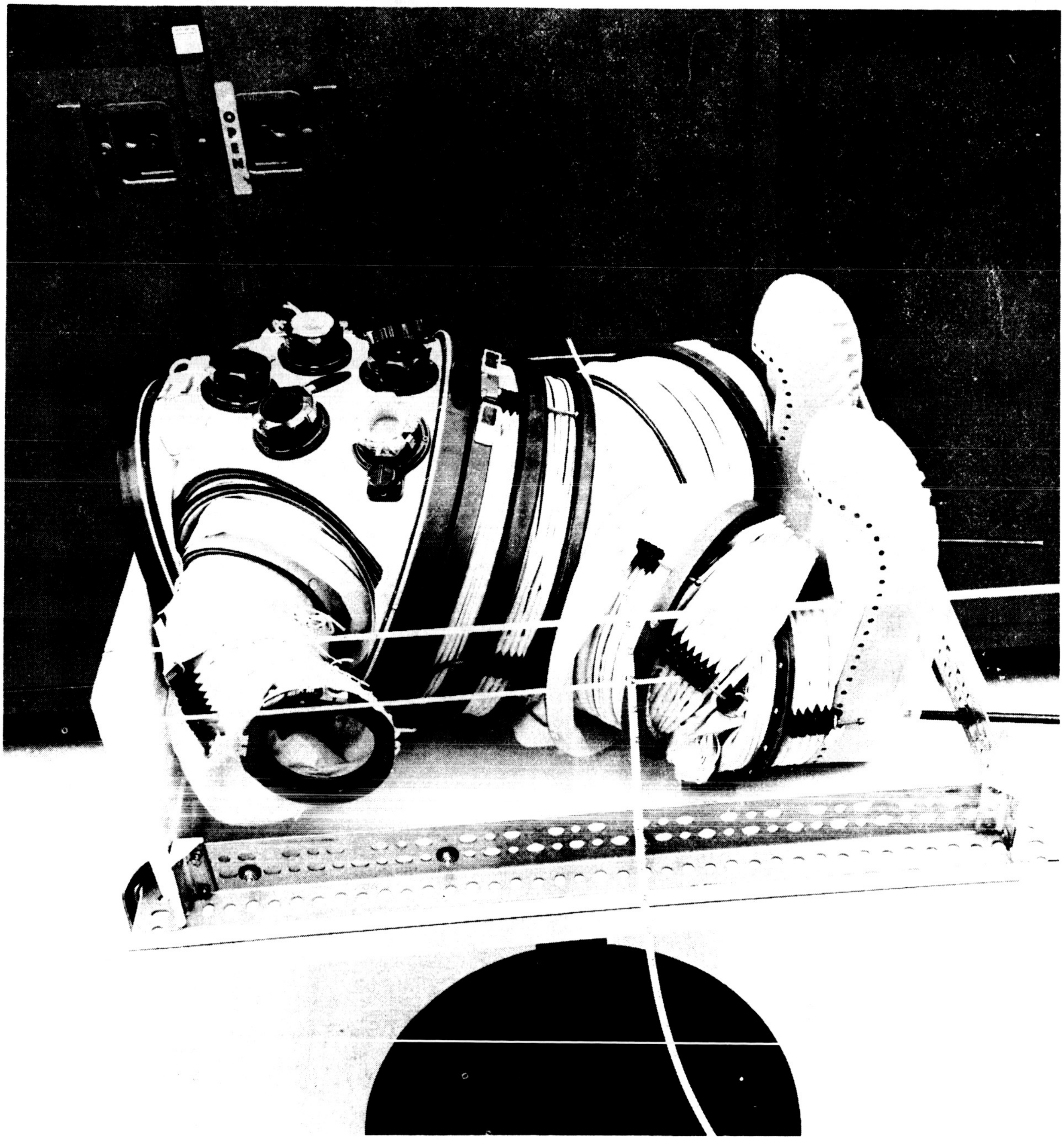


FIGURE A-10: Side View of Suit in Stowage Configuration

APPENDIX B

SOLAR ILLUMINATION CHARACTERISTICS

APPENDIX B

SOLAR ILLUMINATION CHARACTERISTICS

The effects of illumination on a vehicle in space depends on the vehicle's position, the type and source of illumination, and the angular relationships between the vehicle and the source of illumination. These variables are graphically presented in several combinations in Figure B-1. Since the most powerful source of illumination in our solar system is the sun (1.24×10^4 lumens/sq.ft.), a brief discussion of its photometric and geometric characteristics is presented in this Appendix. It is felt that the illumination effects of the earth and moon are relatively insignificant to that of the sun and will, therefore, not be discussed here (ref. B-1).

The light rays from the sun are essentially parallel upon reaching the earth, moon, or any point between the two planets. This is because of the immense distance between the sun and moon or the sun and earth. Slight decollimation is evidenced because of the angular sun size as viewed from the earth to sun distance. This angular sun size is thirty-two (32) arc minutes (ref. B-3).

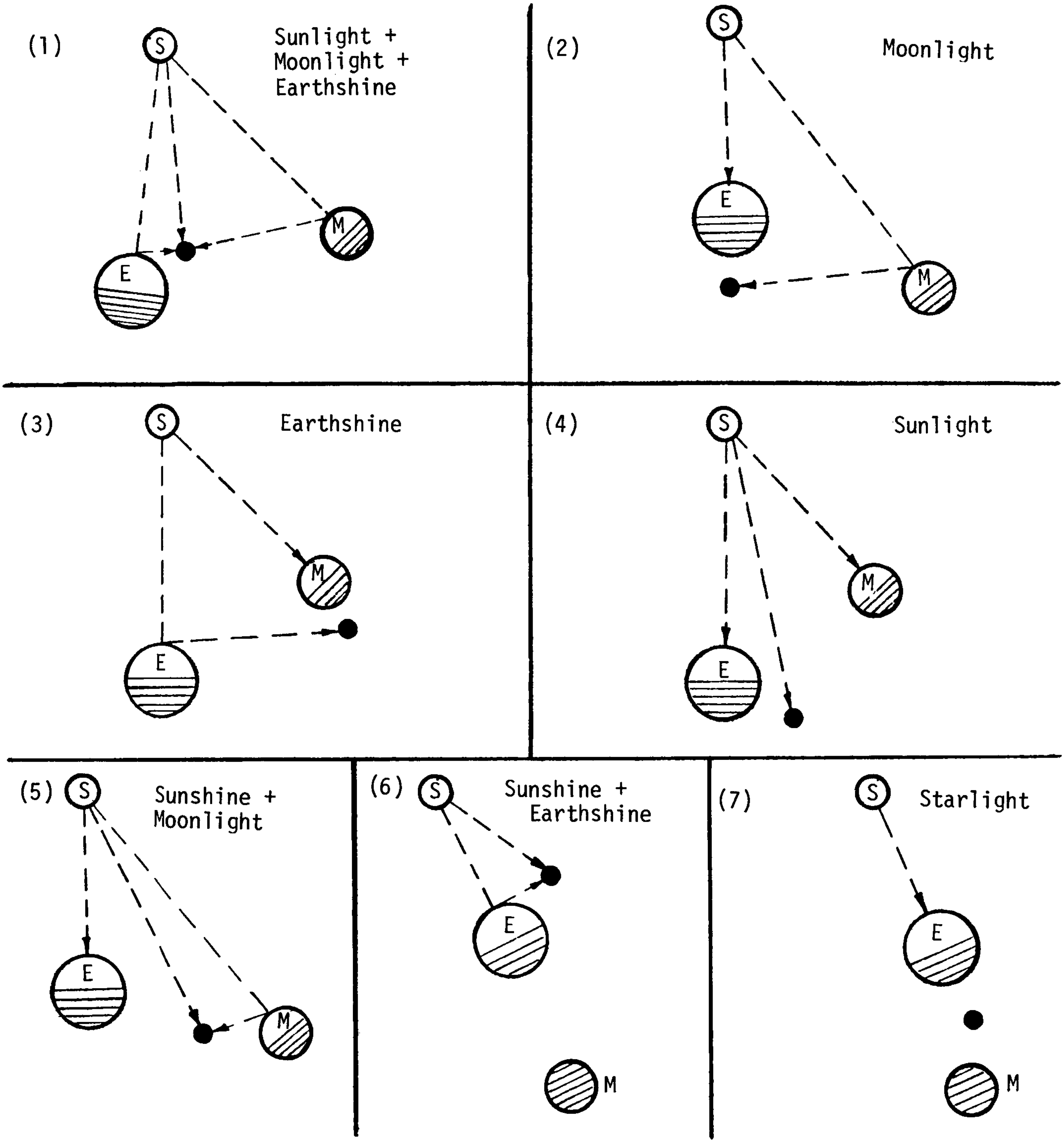
As the angle of incidence of sunlight varies, significant differences in surface characteristics such as shadow shapes, luminance, and color will occur (ref. B-1). These differences will vary with change in angle of incidence and the angle from which the surface is viewed. Changes will also be experienced with different shapes and surfaces. Figure B-2 shows sunlight which is incident against a flat diffuse surface (S) and is viewed at an equal angle of regard (R). The visual angle subtended by this surface (aEc) is a function of the cosine of the angle of regard. In this case, changing the angle of incidence will not change the geometric visual angle (refs. B-1 and B-2).

If the same geometry is applied to a cylindrical shape, the subtended visual angle will vary as a function of the angle between the line of regard and the line of sight. A comparison of Figures B-2 and B-3 shows that, given a fixed viewing position, the visual angle may not be the same for different shapes (plate vs cylinder) depending upon the angle of incidence, even if both objects subtend the same geometric angle (ref. B-2).

The distribution of luminance is also different for the two shapes presented. The flat plate would be uniformly illuminated, whereas the cylinder would not be, due to limb darkening (Figure B-4). Therefore, as can be seen in Figures B-5 and B-6, a plate and cylinder of the same size may appear to subtend different visual angles and have different surface brightness distributions. Questions concerning these figures may arise such as:

- Are the objects at different distances or of different sizes?

- Would different distributions of reflected light provide a means for shape identification or angle of incidence (ref. B-2)?



(NOTE: Black dot is a spacecraft)

FIGURE B-1: Typical Spacecraft Illumination Environments

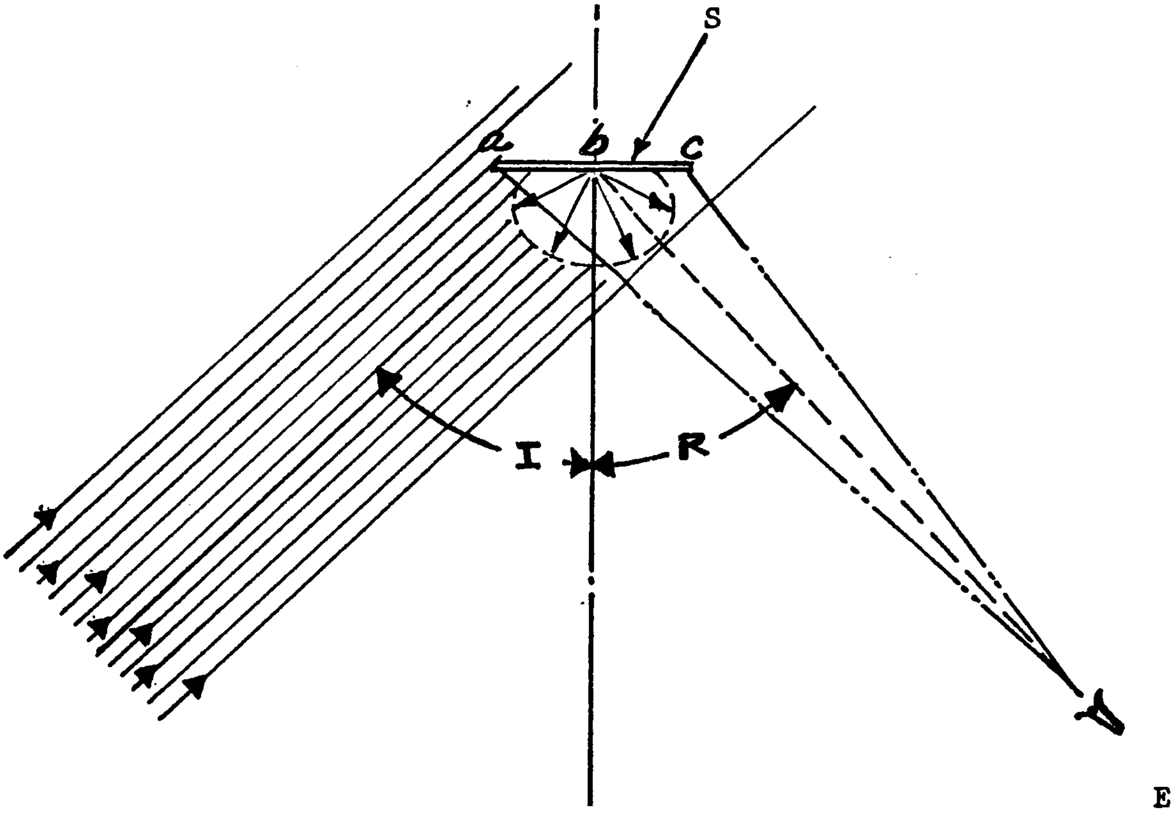


FIGURE B-2: Collimated Sunlight Incident on a Flat Plate

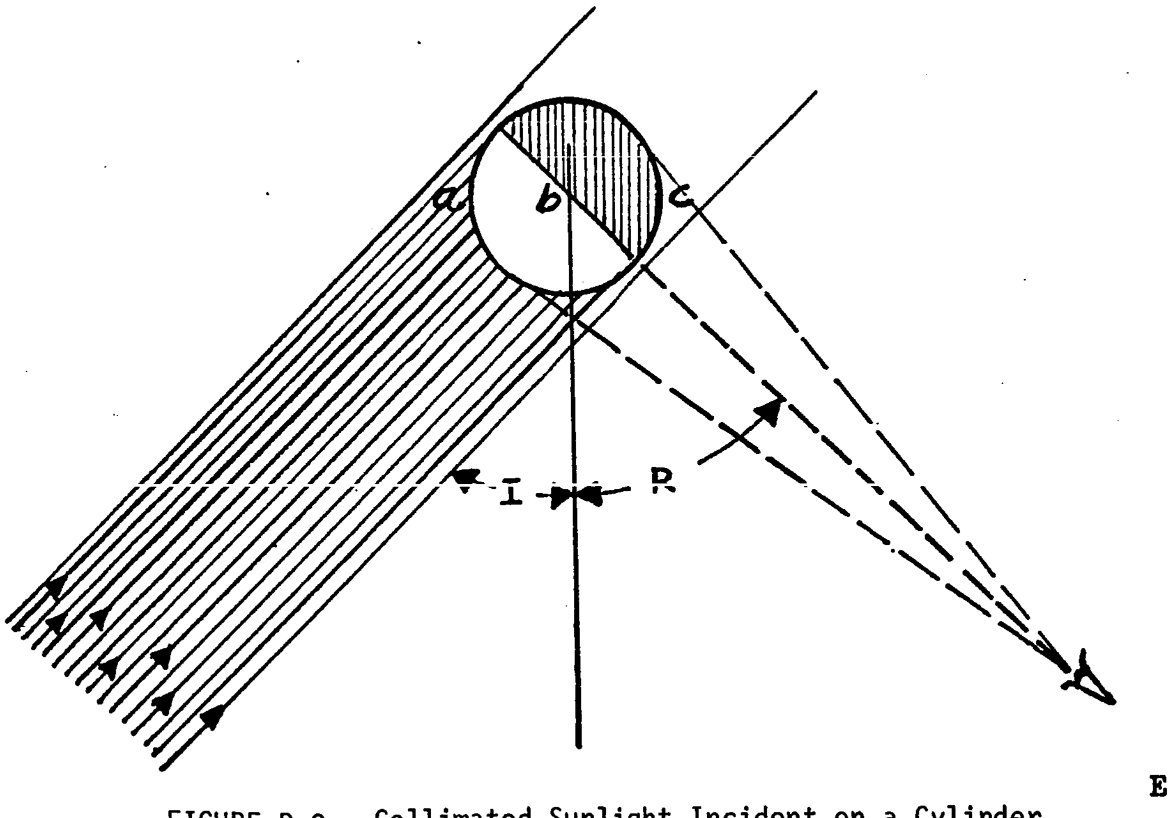


FIGURE B-3: Collimated Sunlight Incident on a Cylinder

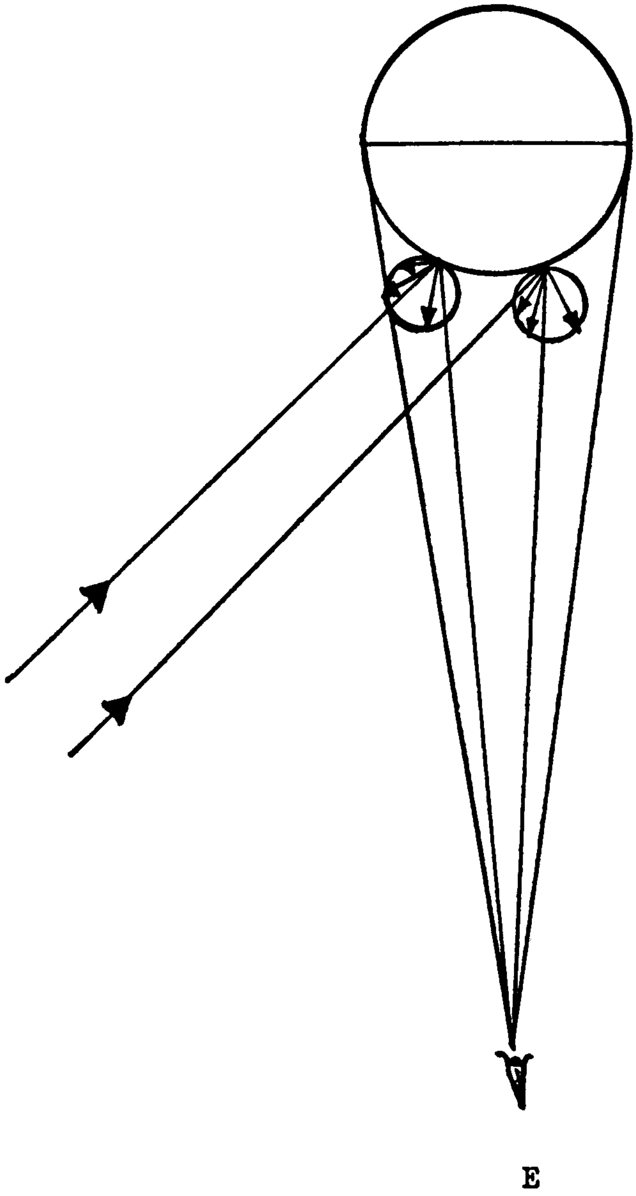


FIGURE B-4: Reflection of Collimated Sunlight from a Diffuse Cylinder Illustrating "Limb Darkening"

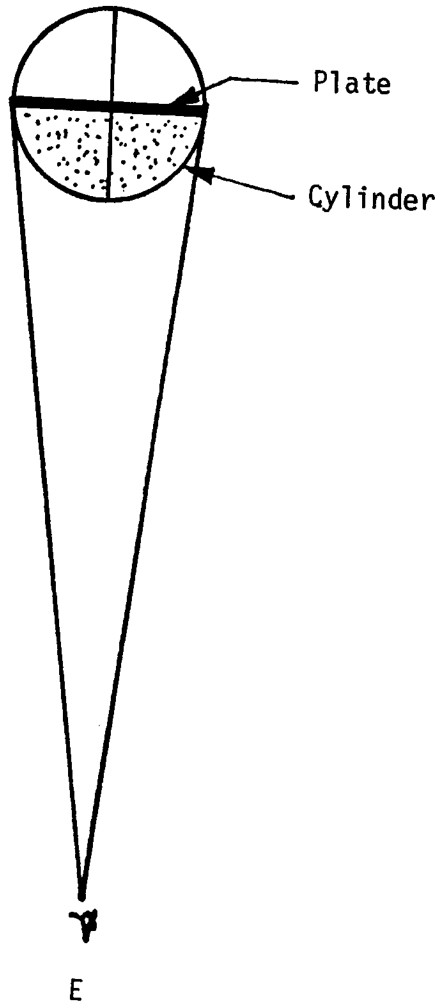


FIGURE B-5: Apparent Angular Size of a Plate and Cylinder Under Diffuse Light

Under diffuse light both a flat plate and a cylinder subtend the same visual angle, but the distribution of reflected light will differ.

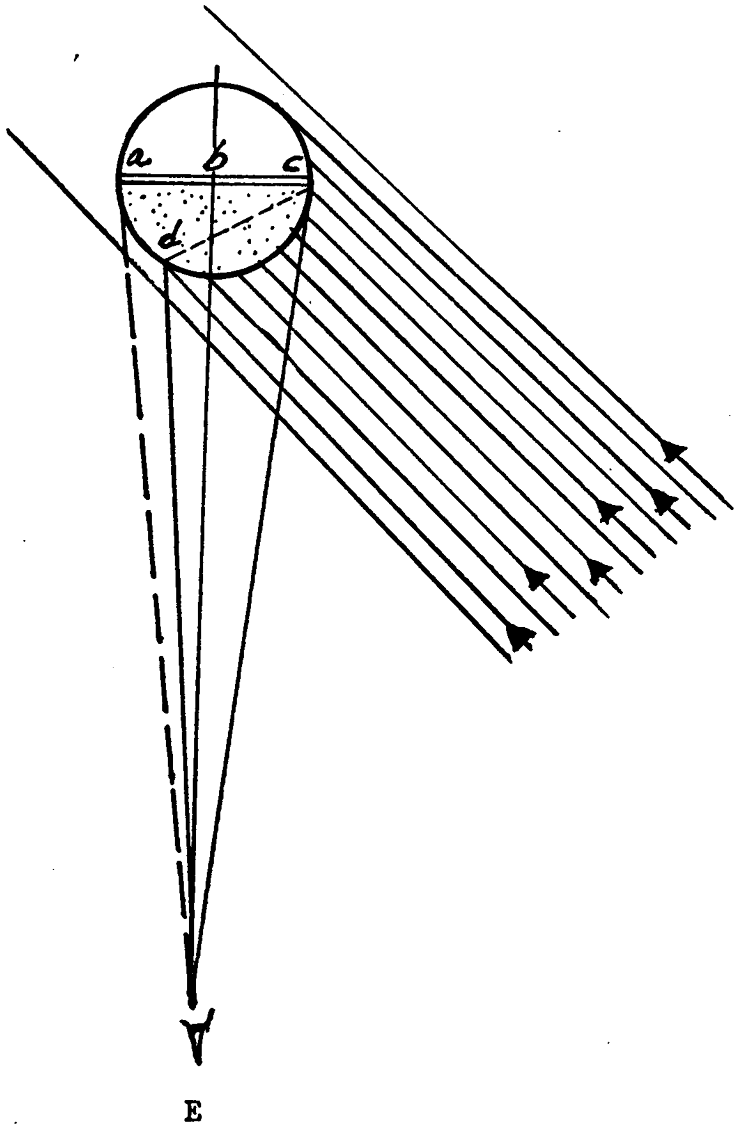


FIGURE B-6: Apparent Angular Size of a Plate and Cylinder Under Collimated Sunlight

With collimated light the plate appears to subtend an angle (aEc) larger than that of the cylinder (dEc).

In considering a specular surface, the angle of reflectance is equal to the angle of incidence. This is shown in Figure B-7. When a collimated

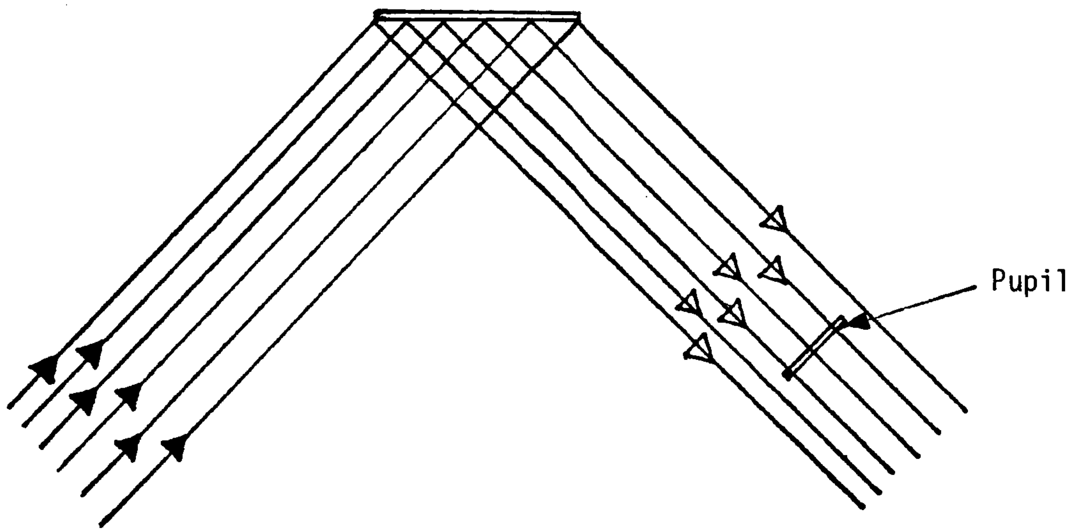


FIGURE B-7: Reflection of Collimated Sunlight from a Flat Specular Surface

beam of light is reflected from a convex specular surface, it will spread, and the viewer will see a thin line of the cylinder (Figure B-8). The remainder of the light would be effectively invisible. This is because the angle of reflectance can be considered relative to a plane tangent to each point of incidence (ref. B-2).

The examples given illustrate that surface reflectance characteristics as well as geometry bear a direct influence on visual geometry. The space produce inconsistent or conflicting stimuli from various points on the vehicle surface (ref. B-2).

The variation of the sun's illumination intensity is so far below the brightness discrimination threshold that it is usually assumed that sunlight is 100% uniform in intensity. This is true for the illuminated surfaces which are observed by the astronaut regardless of the sunlight incidence angle of size of the illuminated area (ref. B-2).

Johnson's solar curve (Figure B-9) is a definition of the spectral distribution of sunlight (ref. B-3). In the space environment, there is neither light scattering by an atmosphere into shadowed areas, nor is there attenuation of the sunlight which illuminates portions of the space vehicles. These effects cause the extreme contrasts encountered during space operations (ref. B-3). Since almost all of the external surfaces of the space vehicle

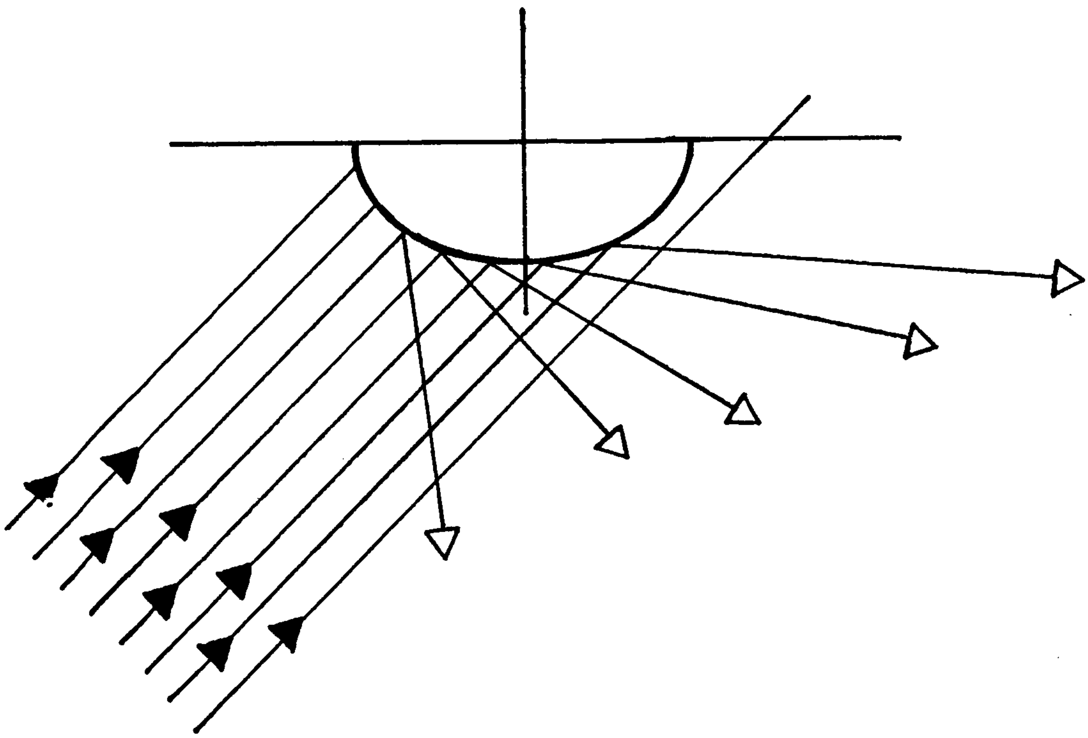


FIGURE B-8: Reflection of Collimated Sunlight from a Curved Specular Surface

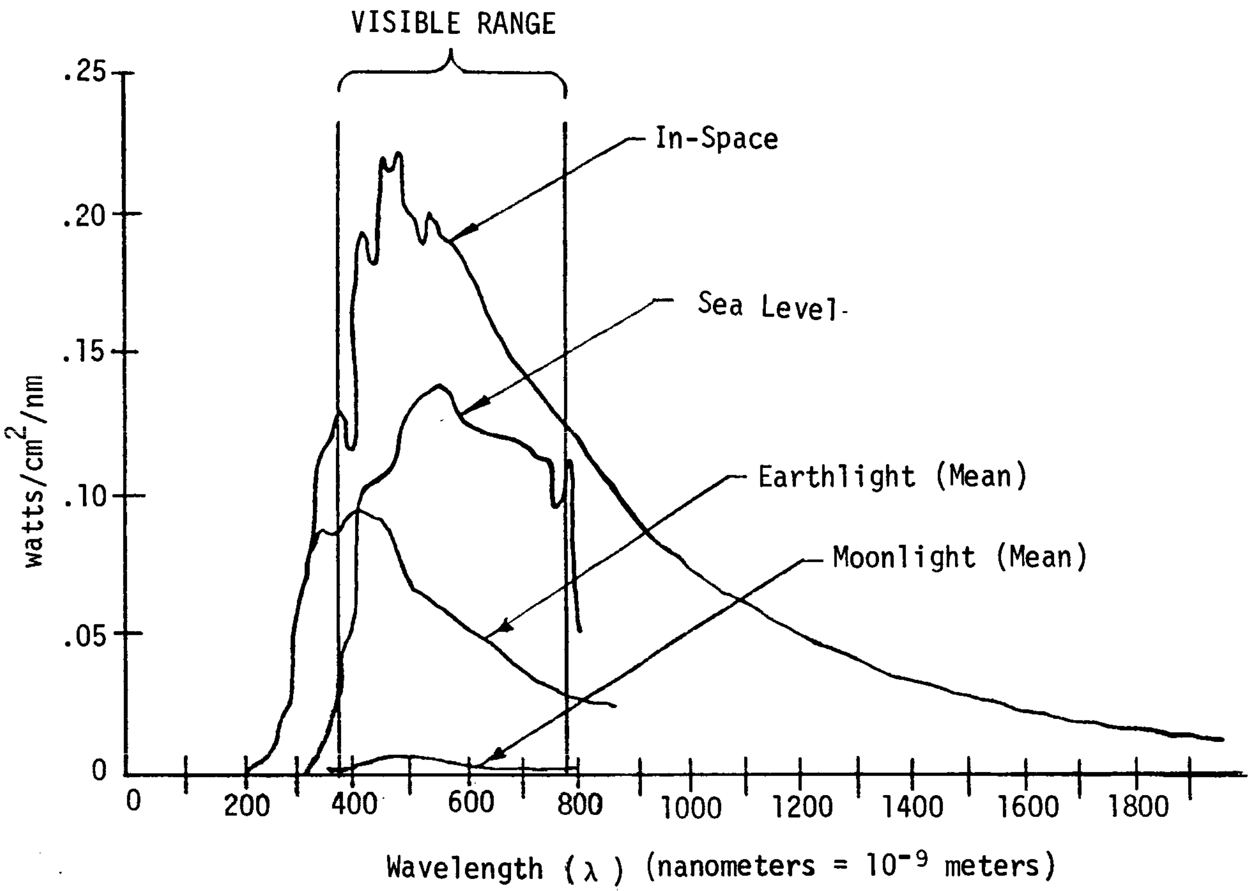


FIGURE B-9: Solar Spectral Energy Distribution

are specular and tend to act as mirrors, it is expected that, for many of the combinations of sunlight incidence angle and astronaut viewing angle, the sunlight will be directed into the astronaut's eyes. If it is not directed into the astronaut's eyes, there is a probability that it could be reflected into the spacecraft windows. The windows would then scatter the light and would "veil" the field of view.

The specularity of the spacecraft's surfaces could alleviate the problem of "fill" lighting, but this could be accomplished only if the vehicles were oriented in such a way that the sunlight was directed into the shadowed areas (ref. B-3).

Skylab EVA Lights

EVA lighting on the Fixed Airlock Shroud (FAS), Deployment Assembly (DA), and ATM assists the crewmen in tasks at the various EVA workstations and illuminates the EVA "trail" (Figure B-10). The EVA lights will be used during each of the six EVAs (ref. B-4).

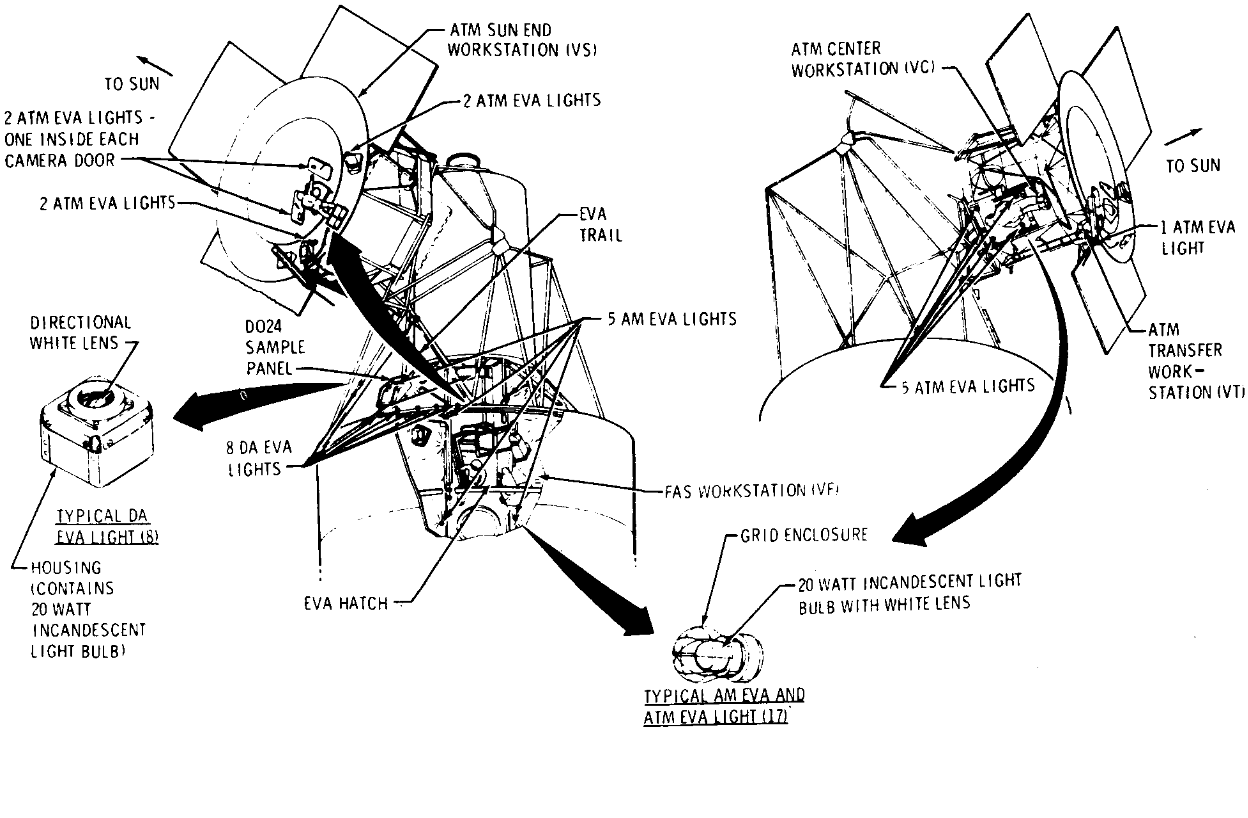


FIGURE B-10: Skylab EVA Lighting

The EVA lights, located on the OWS exterior, provide the necessary illumination as follows:

a. Five AM EVA lights are located around the FAS workstation: four are mounted adjacent to the EVA hatch and the remaining light is mounted on the D024 sample panel handrail. AM EVA lights provide nondirectional lighting of the FAS workstation.

b. Eight DA EVA lights are located around the FAS workstation and along the EVA "trail": four are mounted on the FAS and four on the DA. DA EVA lights serve to illuminate the EVA "trail" with directional lighting.

c. Twelve ATM EVA lights are dispersed at the three workstations on the ATM: five surround the center workstation, one at the transfer workstation, four flank the sun end workstation, and one is inside each camera door at the sun end workstation. With the exception of the camera door lights, ATM EVA lights provide nondirectional lighting of the ATM workstations. The camera door lights provide lighting of the area behind the camera door for camera retrieval and reloading.

The EVA lights are controlled by three switches (Figure B-11) in the lock

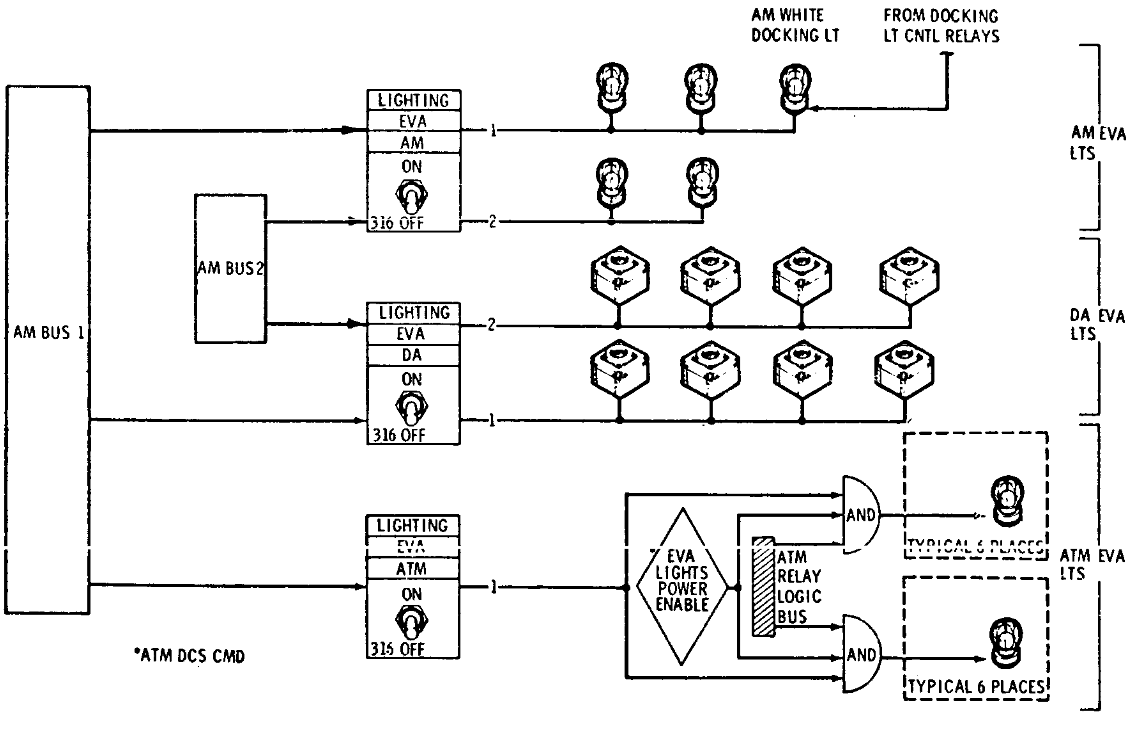


FIGURE B-11: EVA Lighting -- Functional Diagram

compartment on panel 316: the LIGHTING, EVA, AM [ON-OFF] switch controls the five AM EVA lights; the LIGHTING, EVA, DA [ON-OFF] switch controls the DA EVA lights; and the LIGHTING, EVA, ATM [ON-OFF] switch controls the ATM EVA lights (Figure B-11). However, "off" control of the ATM EVA lights is provided by ground commands to assure that the ATM EVA lights are turned off inside the sun end workstation camera doors.

With the exception of the ATM EVA lights, the loss of a single bus will not seriously affect the illumination of a given area. In the case of the ATM EVA lights, DCS commands, coupled with onboard switch control, serve to turn the ATM EVA lights on or off using a single bus.

The AM EVA light on the D024 sample panel handrail is also the AM white docking light. Control of this light for docking purposes is supplied by the docking light control relays which route either a DCS command or the LIGHTING, DOCKING switch command to the light.

REFERENCES

B-1. Kincaid, W. K., Jr. Solar Illumination Simulation, Lockheed Missiles & Space Co., Sunnyvale, Calif., November 1966.

B-2. Lockheed Missiles and Space Co.: Some Aspects of Visual Perception Under In-Space Solar Illumination, Sunnyvale, Calif., no date.

B-3. Kincaid, W. K., Jr., and L. M. Glasser. Apollo Illumination Environment Simulation & Study, Contract NAS9-7661, Lockheed Missiles & Space Co., Biotechnology Div., Sunnyvale, Calif., no date.

B-4. Manned Spacecraft Center: Skylab Operations Handbook, OWS/AM/MDA, Vol. I, MSC 04727, Houston Tex., January 24, 1972.

APPENDIX C

KC-135 ZERO-G AIRCRAFT TESTING REQUIREMENTS

APPENDIX C

KC-135 ZERO-G AIRCRAFT TESTING REQUIREMENTS

Introduction

The primary objective of the Air Force Zero-g Office is to provide a reduced gravity environment for the purpose of conducting test programs sponsored by either DOD or a NASA organization.

Request Procedure

The Zero-g Office is a subdivision of the Aeromechanical Section (ASTDN-10), which is part of the Aeronautical Branch (ASTDN) of the Flight Test Engineering Division (ASTD). The Directorate of Flight Test (AST) is the command authority for all flight testing done at Wright-Patterson Air Force Base (WPAFB) and by WPAFB Aircraft on TDY. This introduction to the chain of command suggests only a few of the channels that proposed programs must clear before they are given authorization to fly.

To initiate the program authorization procedure, it is necessary to submit in writing a letter describing the proposed test. This letter should include, as a minimum, the following:

a. A brief description of the government contract or in-house program generating the requirement.

b. A description of the proposed test including:

- Test objectives
- Test equipment and instrument power requirements
- Test procedures
- AST support requirements
    - photography
    - instrumentation
    - sheet metal
- Possible safety hazards
- Proposed time schedule

The Zero-g Office will hand carry and explain in detail all individual requests to the Programs Division (ASTP). Following ASTP approval, the Zero-g Office will write a test plan addendum to the basic Zero-g Flight Test Plan. Prior to test flying, each program's addendum must be approved by the Commander of Flight Test.

Lead time varies directly with the volume of ASD shop support. Due to such factors as in-house programs, the photographic, instrumentation, and sheet metal shops are booked several months ahead of time for major support items. These facilities are available, however, for "quick fix" emergency items if necessary. When possible, letters of request should precede the data proposed for the initial test flight by six months.

Test Equipment

"Test equipment" includes all items brought aboard the aircraft for test flights (mockups, pressure suits, instrumentation, camera equipment, etc.). MIL Spec MIL-S-5705 requires that all test equipment used in the KC-135 aircraft be stressed for g-forces as follows:

16g forward

8g down

4g up and laterally

1.5g aft

In constructing tests, designers should use the following guidelines:

a. Make the test program flexible in design, and consult frequently with the Zero-g Office in order to prevent last minute changes.

b. Submit rough sketches of test equipment and mockups to the Zero-g Office prior to the making of construction drawings. At this point, it is easier to make alterations to insure safety and smooth operation during test flights. When making initial sketches, test designers should:

- Avoid sharp corners on all mockups and test equipment.
- Avoid using wood anywhere in test equipment; if possible, equipment should be mounted in a welded aluminum framework.
- Design equipment for ease of mounting. On large pieces, air bearings and/or flat plates should be employed on the base. Heavy duty handles and holes at several locations around the base just above the floor for fork list arms or J-bars should be provided on all equipment. Handles are especially important on equipment that is to be free floated.
- Avoid excessive moments by keeping equipment height to a minimum and by providing a sufficiently large base.
- Design equipment in such a manner that the rigid tying together of several pieces (forming a cantilever of ten or more pieces) is not necessary. Such configurations

would inhibit flexure of the aircraft's fuselage and distribute strain unevenly.

- Recognize that the Zero-g Office is in charge of aircraft layout and test equipment installation. On occasion, one test program may have to share the aircraft with another program. When this must be done, an attempt will be made to fly projects that are compatible with each other.

- Keep test programs on an unclassified level, whenever possible.

- If equipment requires electrical power:

  - avoid exposed terminals and connectors
  - provide fuse or circuit breakers in all circuits
  - avoid setting up equipment with laboratory plugs (cannon type plugs that are compatible with aircraft power distribution boxes will be provided by the Zero-g Office)
  - use a gauge of wire compatible with fuses and circuit breakers.

- Avoid the use of dangerous fluids.

Following are a few additional hints which will not directly affect equipment design, but which may prove helpful in preparing for a test series:

- Equipment should be designed with at least 3/4" mounting holes in the base, drilled for a 20" mounting grid.

- Everything in the aircraft is subject to the same g-forces. If a test is to be conducted at zero-g, everything in the aircraft will float. Eliminating clip boards, briefcases, pencils, etc., before the flight saves delaying the flight to retrieve them or looking for them after the flight.

- The assistance of test program personnel in loading/unloading test equipment at the appropriate time will be appreciated.

- Although the Zero-g Office has no tools available, electrical power and work bench space for checkout of test equipment is furnished. Individual programs must provide their own tools and whatever materials are required for normal maintenance of test equipment.

- A program's first flight will be made only after the Zero-g Office is satisfied that it will be a safe, well-organized flight.

Responsibilities

First in importance is that all persons coordinate all their activities and cooperate with each other. Effective lines of communication do more for efficient operation than any other single item. Pertinent information about the Zero-g Office is listed below:

Office Personnel

Mr. Donald Griggs	Zero-g Test Director
Mr. James A. Lackey	Assist. Zero-g Director
Joyce A. Campbell	Office Secretary

Office Telephone Extensions

Commercial Calls:	257-2606,	257-3805,	257-0040
Autovon Calls:	787-2606,	787-2805,	787-0040

Office Location

ASTDN-10/Zero-g Test Office
Room 5, Building 110, Area C, WPAFB

Official Mailing Address

Aeronautical Systems Division
Wright-Patterson Air Force Base, Ohio 45433

It is the responsibility of the requesting agency to insure that all test equipment conforms to the standards mentioned earlier. If test equipment is delivered to the Zero-g Office in an unsatisfactory configuration, the test series will be delayed until the necessary modifications can be made. This can be prevented by consulting this office prior to the construction of test equipment.

The success of any test series depends largely on the mutual cooperation of all parties involved. The Zero-g Office will do its best to promote a good test series, if it enjoys cooperation in preparing for each flight.

Each test program is assigned a priority by Headquarters AFSC. Should there be a conflict in the scheduling of two different programs, the one with the higher priority will take precedence in resource utilization.

Once a program is approved, the test equipment is satisfactory, and the program test plan is approved, a flight test series can be scheduled. Normally, the first flight test series with new test equipment will be limited

to two or three flights in a week's (Monday - Friday) time. At least two weeks prior to the first test flights, a test plan should be submitted to the Zero-g Office, outlining what will be attempted during test flights. In drawing up the test plan, please keep in mind that this first flight will probably accomplish only an equipment shakedown. Successive flights will be more productive as procedures are learned, new people become acclimatized to zero-g, and test equipment is debugged. It is suggested that the test personnel collect the most important data at the beginning of each flight and allow for some overlap in data collection between flights. The first flight of a series, if it includes first time personnel or equipment, should be no more than 20 maneuvers. Subsequent flights and later test series can adopt a more ambitious flight schedule once initial problems are overcome.

Test equipment to be used during the test series should arrive in the Zero-g Office (ASTDN-10) no later than a week before flights are to begin. Shipments should be sent to this office as previously listed. Shipments will be received only between 0715 and 1600 hrs., Monday through Friday. Test flights will normally be scheduled at 1000 hrs., with the flight briefing taking place beforehand at 0830 hrs. in the Zero-g Office. The office must notify maintenance personnel that someone will be working on the aircraft.

After each flight series, please put the Zero-g Office on the distribution list for a copy of the test report and edited film. At the completion of the project, a copy of the final technical report should be submitted to the Zero-g Office for filing purposes. This will allow the office to complete its final paperwork and to help prevent a future duplication of effort.

All personnel who will participate in test flights must have flying orders cut by Aeronautical Systems Division. Once an individual has satisfied the requirements listed below, forward to the Zero-g Office appropriate forms showing the completion of the following training:

1. Altitude Indoctrination
2. Survival Training
3. Air Force Class III or FAA Class II Physical
4. Security Clearance

This office will request the individual's orders, and it will take approximately one week for the orders to be processed. The Zero-g Office must have the paperwork of each individual who is expected to fly in support of a program at least a week before the initiation of testing. The duration of individual flight orders will be in accordance with ASD Regulation 60-1 (subject to change). To renew flight orders, all paperwork must be resubmitted.

Each individual must provide his own boots. Any heavy-duty lace or buckle type boots that cover the ankle will suffice. Once ASD has cut an individual's orders, he will be permitted to check out a flying suit from the personal

equipment section for the duration of the test series or a maximum of one week. Compliance with the turn-in dates requested by the issuing organization is appreciated.

Each aircraft will have enough parachutes and oxygen (O_2) masks for use in case of emergencies. Life preservers will be provided if overwater flight is anticipated. It is an individual responsibility to become familiar with the operation of this emergency equipment and to learn how to exit the aircraft in an orderly manner should an emergency occur. A copy of KC-135 Emergency Procedures will be available for study purposes prior to the test series. Before a first flight, everyone must pass a test, administered by the Bomber Operations Division, on these emergency procedures.

Aircraft Specifications

The KC-135 aircraft dimensions shown in Figures C-1 through C-4 are to be used only as a general guideline when designing and constructing test equipment. Equipment should not be sized to just clear the cargo door or fuselage cross section. Several inches of clearance are required to facilitate equipment loading and installation. Equipment should be made as mobile as possible.

A standard Air Force AIC-18 interphone network is used on the aircraft for communications during test flights. One person from the Zero-g Office will be appointed test director for each flight, and he will be responsible to the aircraft commander for all test activities in the rear of the aircraft. The test director will be in contact with the pilots and will relay pertinent communications to all test personnel. Test personnel will be on a separate private interphone circuit. Key test personnel will be on a hot microphone that does not require pressing the mike button to transmit. Others who must monitor communications will be on a press-to-talk circuit. Due to excessive aircraft background noise and the need for clear communications in case of an emergency, the number of test personnel on interphone circuits will be held to a minimum. Each individual on a headset will help reduce confusion and increase the efficiency of each flight if he holds his talking to a minimum and keeps his interphone cord from fouling test equipment or other cords.

When a test involves one or more test subjects in a pressure suit, it is mandatory that the intercom circuiting be checked out prior to each flight. Reliable communications with all pressure suited subjects is a prerequisite for each flight. Flights will be cancelled or terminated early if satisfactory communications cannot be maintained. The personnel responsible for the pressure suits should conduct an interphone check at least one day before each flight in order to allow for repairs that may be required.

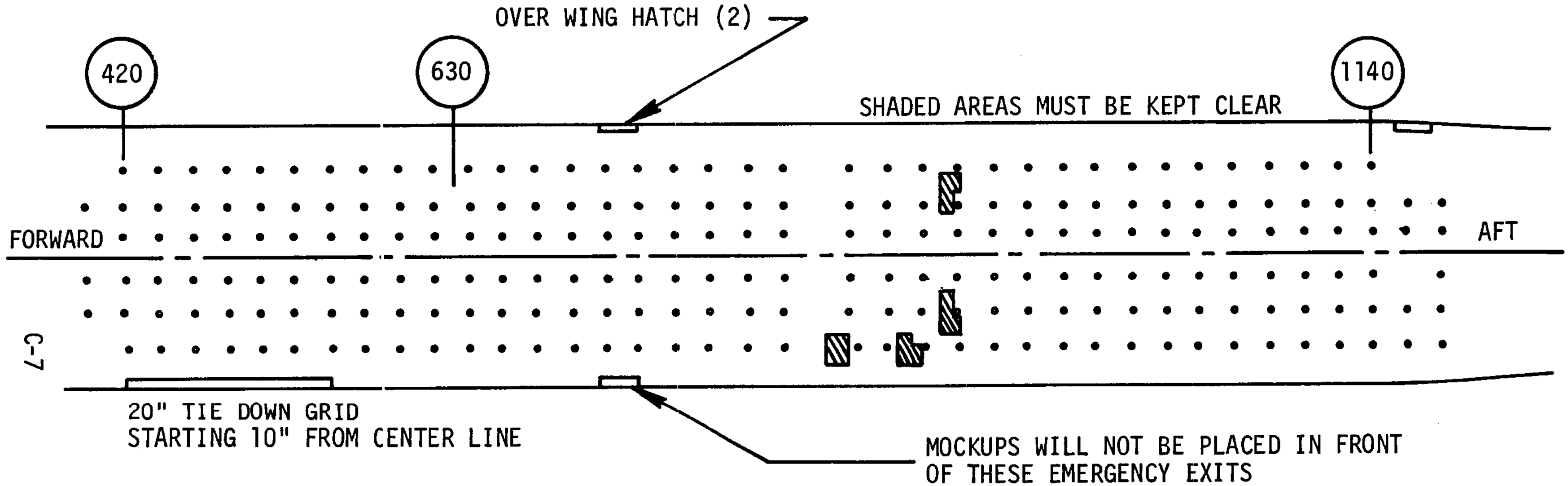


FIGURE C-1: Top View of KC-135 Zero-g Aircraft

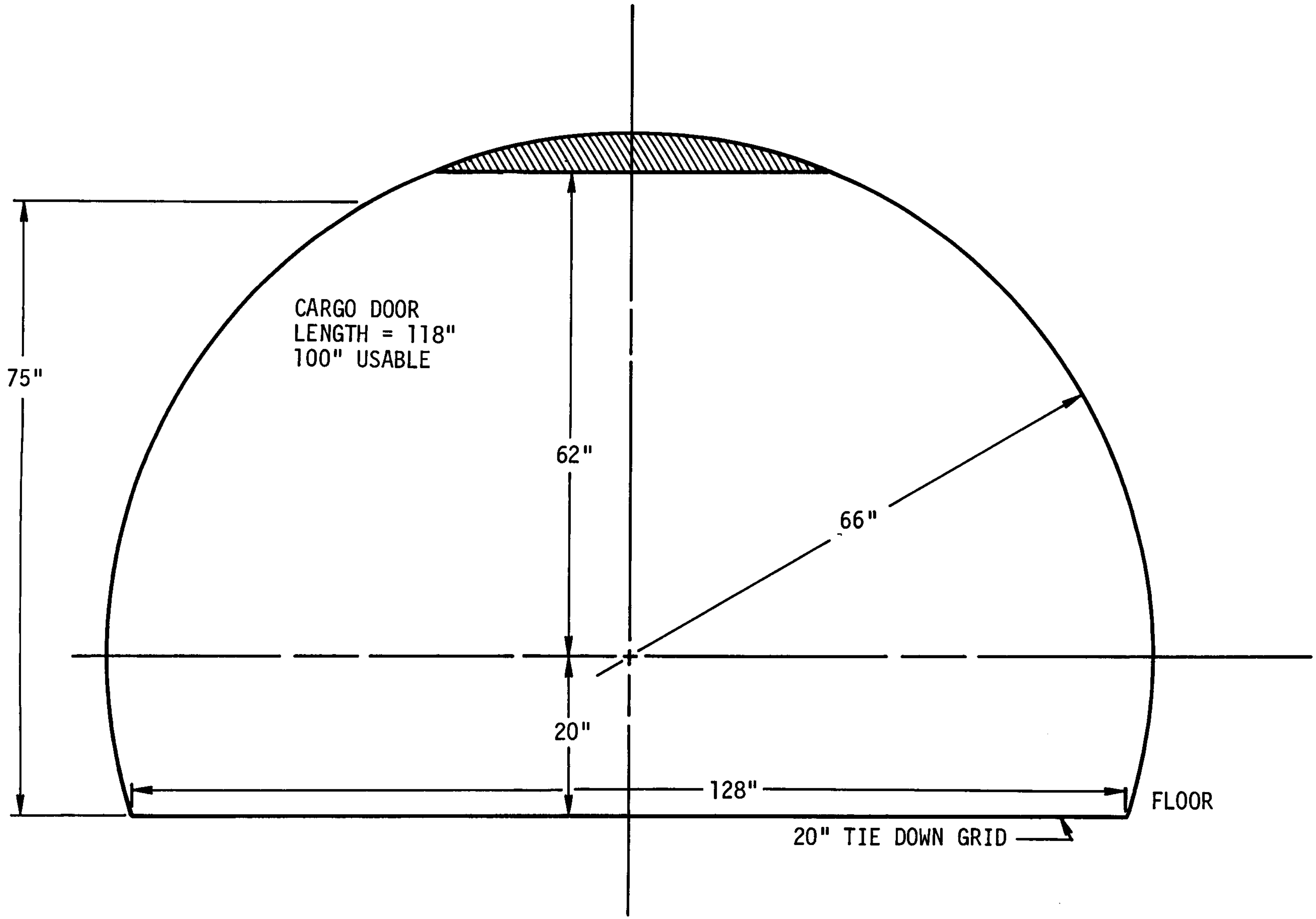


FIGURE C-2: Cross Section View of KC-135 Stations 420-590 (Looking Forward)

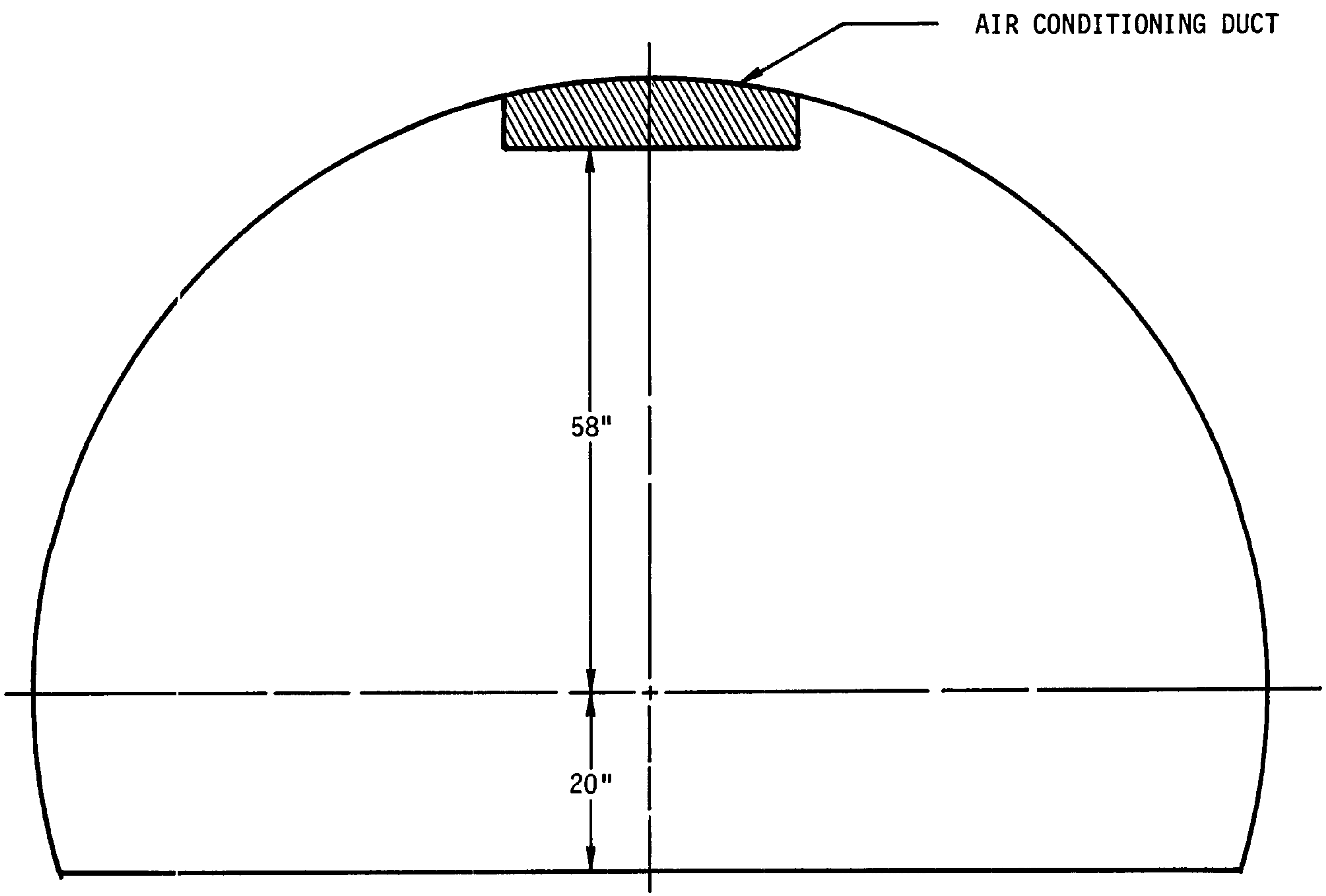


FIGURE C-3: Cross Section View of KC-135 Station 630 (Looking Forward)

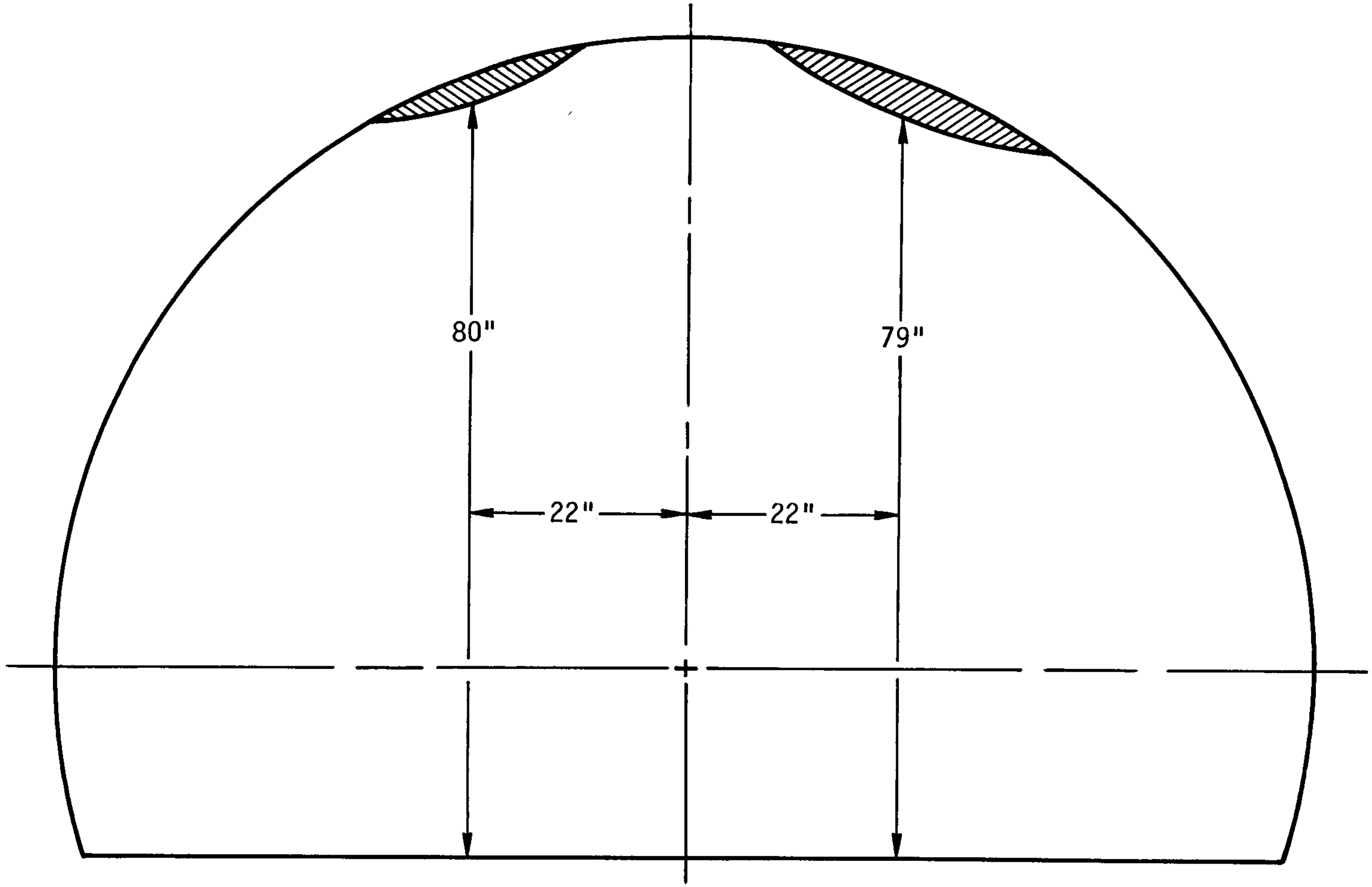


FIGURE C-4: Cross Section of KC-135 Stations 630-1140 (Looking Forward)

APPENDIX D

SUMMARY OF SPACEFLIGHT MEDICAL EXPERIENCES

APPENDIX D

SUMMARY OF SPACEFLIGHT MEDICAL EXPERIENCES

INTRODUCTION

Although man has shown considerable variation in his ability to tolerate certain geograhic extremes, the space environment offers him none of the physical attributes which he requires for survival, physiological comfort and effective work performance. Therefore, of primary importance in the astronaut's training, in his spacecraft and space suit life support systems, and in ground surveillance during spaceflight missions are securing man's safety and providing for his effective functioning while exposed to the stresses of acceleration, weightlessness, heat, noise, vibration, confinement and radiation. Of equal importance is determining man's responses to the space environment. These two tasks -- protecting man from this environment and determining his reactions to it -- are the major goals of space medicine.

Space medicine is involved in several areas of study, among them being the selection of crews; monitoring these crews during test procedures (such as altitude chamber, suit, and related equipment tests, underwater simulations and centrifuge runs; preparing them for flight; determining their fitness on a continuing basis; and measuring the crews inflight and postflight responses.

In Chapter 5, "Orbital EVA Human Performance and Biomedical Characteristics", space medicine's role during extravehicular activity is examined. In this appendix, additional summary information on the overall medical experience gained from the United States' manned spaceflights is presented, and biomedical experiments for the Skylab missions are discussed. It should be noted that the information contained in this appendix was derived from the numerous articles, publications, reports, and presentations of NASA personnel located in the Office of Life Sciences, Washington, D. C., and from mission reports of manned U. S. spaceflights. The NASA Office of Life Sciences personnel, whose documentation was used most liberally, include: Charles A. Berry, M.D., Director of NASA Office of Life Sciences (former Director of Medical Research and Operations Directorate, Manned Spacecraft Center); Col. Rufus R. Hessberg, Director - Space Medicine; Dr. Edward J. McLaughlin, Deputy Director - Space Medicine; and Dr. Stanley Deutsch, Director - Bioengineering.

MEDICAL EXPERIENCE IN MANNED SPACEFLIGHT

Man has made rapid steps into the troposphere, stratosphere and space equivalent regions beyond. To date, developing the capability to place man into space and assuring that he and his life sustaining equipment function for the duration of the mission have been of utmost importance. Although early theories concerning space travel predicted catastrophic failures of various organisms' vital functions when thrust into an environment without a gravitational force, the first orbital flights by animals proved these theories

invalid. The Mercury program, while demonstrating that man could successfully live and carry out operational mission tasks for brief excursions into space, provided evidence that man underwent physiologic changes much like those observed in man under simulated conditions (e.g., prolonged bed rest or water immersion).

Early Mercury missions were of relatively short duration, lasting 15 minutes at first to about 34 1/2 hours. In attempting to extend the mission length at a safe pace, the Gemini program utilized the technique of doubling mission length: 4 days, 8 days and 14 days. Before exposing man to the next flight duration increment, detailed findings and performance were closely examined. At that time, the aim was to qualify man for lunar missions. Physiological changes were observed as a function of duration of exposure for crewmen on each flight. With knowledge gained of the mechanisms of these changes in man's systems, subsequent studies on longer flights evolved.

The summaries of the manned flight missions thus far completed (Mercury, Gemini, and Apollo flights) are contained in Tables D-1 through D-3. Specifically, 34 men have flown 26 missions for 56 man-exposures totaling some 7039:05 man-hours of spaceflight. One person has flown in the 1-, 2-, and 3-man spacecraft (Mercury, Gemini and Apollo, respectively); 3 persons have flown both in the Mercury and Gemini spacecraft; 4 persons have flown twice in the Gemini spacecraft; and 2 persons have flown twice in the Apollo spacecraft. Fourteen persons have flown in Gemini and Apollo spacecraft. Mission durations have been 1 of 14 days, 1 of 12 days, 2 of 11 days, 2 of 10 days, 1 of 9 days, 3 of 8 days, 2 of 6 days, 2 of 4 days, 3 of 3 days, and 9 of 34 hrs., or less. The exposures indicated in the few thousand hours of manned spaceflight experience form the basis for the following discussion and conclusions.

TABLE D-1: Mercury Manned Flights

Flight	Crew	Launch	Description	Duration
				hr:min
MR-3	Shepard	5/5/61	1st manned (suborbital)	0:15
MR-4	Grissom	7/21/61	2nd suborbital	0:15
MA-6	Glenn	2/20/62	1st orbital	4:50
MA-7	Carpenter	5/24/62	2nd orbital	4:56
MA-8	Schirra	10/3/63	3rd orbital	9:14
MA-9	Cooper	5/15/63	4th orbital	34:20
Total				53:56

TABLE D-2: Gemini Manned Flights

Flight	Crew	Launch	Description	Duration
				hr:min
G-III	Grissom and Young	3/23/65	3rd revolution manned test	4:52
G-IV	McDivitt and White	6/3/65	1st extended duration and EVA*	96:56
G-V	Cooper and Conrad	8/21/65	1st medium-duration flight	190:56
G-VII	Borman and Lovell	12/4/65	1st long-duration flight	330:35
G-VI	Schirra and Stafford	12/15/65	1st rendezvous flight	25:53
G-VIII	Armstrong and Scott	3/16/66	1st rendezvous and docking flight	10:41
G-IXA	Stafford and Cernan	6/3/66	2nd rendezvous and docking, 1st extended EVA	73:04
G-X	Young and Collins	7/18/66	3rd rendezvous and docking; 2 EVA periods; 1 docked Agena-propelled high apogee maneuver	70:40
G-XI	Conrad and Gordon	9/12/66	1st rendezvous and docking initial orbit; 2 EVA periods; 2nd docked Agena-propelled high apogee maneuver; tether exercise	71:17
G-XII	Lovell and Aldrin	11/11/66	Rendezvous and docking; umbilical and 2 stand-up EVA periods; tether exercise	94:37
Total Gemini man-hours in space				1939:14

*EVA = Extravehicular activity.

In evaluating the results of these exposures of man to the spaceflight environment, it is important to recognize that each crewman in flight is being exposed simultaneously to multiple stresses, and that it is difficult to evaluate the stresses singly, either inflight or postflight. A summary of these stresses is shown in Table D-4.

TABLE D-3: Apollo Manned Flights

Flight	Crew	Description	Duration
			hr:min
Apollo 7	Schirra, Eisele, and Cunningham	Earth orbital checkout of CSM systems	260:9
Apollo 8	Anders, Borman, and Lovell	Lunar orbital mission of CSM systems (TLI, LOI, TEI checkout)	147:0
Apollo 9	McDivitt, Scott, and Schweickart	Earth orbital checkout of CSM-LM systems (LM-CSM separation and docking)	241:0
Apollo 10	Stafford, Young, Cernan	Lunar orbit, separation docking descent	192:03:23
Apollo 11	Armstrong, Aldrin, Collins	First lunar landing	195:18:35
Apollo 12	Conrad, Bean, Gordon	Second lunar landing	244:36:25
Apollo 13	Lovell, Haise, Swigert	Third lunar landing (abort due to explosion)	142:54:41
Apollo 14	Shepard, Roosa, Mitchell	Fourth lunar landing	216:01:58
Apollo 15	Scott, Worden, Irvin	Fifth lunar landing	295:11:53
Apollo 16	Young, Mattingly, Duke	Sixth lunar landing	265:51
Total Apollo man-hours in space*			6600:21
Total man-hours in space**			8539:35

* Mission duration x number of crewmen.
** Includes Mercury, Gemini, and Apollo.

Some of these stresses can be simulated in ground based studies, and this has been done many times. Nevertheless, the actual flight situation has not been duplicated because weightlessness and the emotional stress of flight are impossible to duplicate in ground studies.

TABLE D-4: Spaceflight Stresses

Full pressure suit
Confinement and restraint
100% oxygen = 5 psia atmosphere
Changing cabin pressure (launch and entry)
Varying cabin and suit temperature
Acceleration-G force
Weightlessness
Vibration
Dehydration
Flight plan performance
Sleep need
Alertness need
Changing illumination
Diminished food intake (varying with crewman)

Crew Monitoring

Continuous monitoring of physiologic data is necessary to provide information flight objectives, to assure safety of the crew during the flight, and to obtain information by which to predict the effect of extended duration flight on man. To obtain a set of physiologic indices, the crewman's voice, two leads of his electrocardiogram, his respiration, body temperature, and blood pressure have been monitored in the manned flight program (see Table D-5).

Much has been learned about the use of minimal amounts of data obtained at intermittent intervals while a spacecraft is over a particular station, as in earth orbital flight. On the lunar missions, ground monitors have virtually constant contact with the spacecraft, but the data are again, intermittent. During the early Apollo missions, electrocardiogram and respiration data were obtained on one astronaut at a time through a manually rotated switch aboard the spacecraft. Later Apollo flights were capable of transmitting information on all three crewmen simultaneously and did so usually only during launch, EVAs, and reentry. Monitoring of the EVA astronaut is discussed in Chapter 5.

Sensors and the biomedical harness have been modified slightly from program to program. However, sensors and associated equipment are designed to interfere as little as possible with the comfort and function of the crew. Whenever possible, data procurement has been virtually automatic, requiring little or no action on the part of the crewmen.

TABLE D-5: Physiologic Parameters Monitored During Mercury, Gemini, and Apollo

PROGRAM	DATA RETRIEVAL SYSTEM	PARAMETERS	INSTRUMENTATION
Mercury	Telemetry	ECG, sternal lead	Bipolar electrodes
		ECG, axillary lead	Bipolar electrodes
		Blood pressure	Automatically inflated cuff, microphone pickup of Korotkow sounds
		Body temperature	Rectal thermistor (changed to oral thermistor for MA-9)
		Respiratory rate	Heated wire bridge replaced by impedance pneumograph on MA-8 and MA-9
Gemini	Telemetry	ECG, sternal lead	Bipolar electrodes
		ECG, axillary lead	Bipolar electrodes
		Blood pressure	Manually inflated cuff, microphone pick-up of Korotkow sounds
		Body temperature	Oral thermistor
		Respiratory rate	Impedance pneumograph
	Onboard recorder	EEG, 2 leads (Gemini VII, Command Pilot)	Electrodes cemented to scalp
		Phonocardiogram (Gemini IV, V, VII, Pilot)	Parasternal microphone
Apollo	Apollo 7 & 8: one crewman selectable - tele.	ECG sternal lead Respiratory rate	Bipolar electrode Impedance pneumograph
	Apollo 9-14: three crewmen, simultaneously - tele. (CM) Apollo 13: one crewman selectable due to abort	ECG sternal lead Respiratory rate - oral temperature on demand	Bipolar electrode Impedance pneumograph
	Apollo 15 & 16: three crewmen simultaneously	ECG sternal lead Respiratory rate	Sponge/pellet electrode Impedance pneumograph

Crewmen have suffered varying degrees of skin irritation at the biomedical sensor sites. Minor problems with the sensors have caused temporary signal loss, but the crewmen have corrected the problems with additional electrode paste, removal/replacement of the sensors, and reconnection of sensor wire.

Cabin Atmosphere

In relating experience with aircraft in the earth's atmosphere to the vacuum of space, difficulty in maintaining cabin pressure was predicted. Space vehicles have consistently maintained cabin pressure of approximately 5 pounds per square inch throughout the manned flights to date.

There was concern about the provision of an adequate oxygen atmosphere and about whether the 100% oxygen at 5 psia would prove to be a hazard. Altitude chamber tests of this atmosphere were made prior to inflight use. Through Gemini flights, ample oxygen had always been available, the only identified effect on man from this environment being the red blood cell changes discussed in a later section of this appendix.

In January 1967, while the first manned Apollo spacecraft was being tested on the launch pad with a 16 psia 100% oxygen environment, a fire occurred causing the death of the crew. This resulted in a change in cabin atmosphere during the launch phase of the Apollo spacecraft. Instead of 100% oxygen, the cabin was filled with a 64% oxygen, 36% nitrogen atmosphere. This figure represented the least amount of oxygen which would provide a safety margin in view of the tolerances of the oxygen regulators and cabin relief valves.

It was estimated that the minimum alveolar partial pressure of oxygen (ppO_2) obtained would place the crew in breathing air the equivalent of that found at an altitude of 4000 feet. During the first two missions, the cabin, monitored by a ppO_2 sensor, never reached an alveolar equivalent above sea level. Another item of importance with this atmosphere was the very slow buildup toward a 100% oxygen cabin atmosphere. During the 11-day Apollo 7 mission, the cabin never reached a ppO_2 above 93%. This oxygen-nitrogen atmosphere has proved to be exceedingly safe while at the same time reducing the fire hazard.

Reduction in cabin pressure to 5 psia, equivalent to a pressure altitude of 27,000 feet, created concern about the possible development of decompression sickness. During the Mercury and Gemini series, the astronauts received two hours of denitrogenation before flight by breathing 100% oxygen. Coupled with the further denitrogenation accomplished in the spacecraft, this proved to be ample protection.

Further chamber studies following the Gemini program showed that a minimum of three hours of denitrogenation is necessary to provide the best protection against decompression sickness. Apollo crews have prebreathed for a three hour period on 100% oxygen, including time on the launch pad. Once the cabin has reached 5 psia with the 60/40 atmosphere, the crew is

still protected against decompression sickness, even when breathing this atmosphere, provided they have been adequately denitrogenated preflight. This method has prevented the development of decompression sickness on any mission thus far.

The need to maintain cabin temperature was also a matter of concern. Temperature was maintained at approximately 70°F, varying between 62° and 80°F, except for a few instances when the crew became cold as the spacecraft was powered down.

Apollo astronauts have removed space suit helmets and gloves usually within the first half hour and always within the first hour after launch. Space suit doffing was completed when convenient, and flight coveralls donned for the major portions of the missions. In the Apollo 7 missions, the crew donned their space suits to check their capability to do so and their reentry configuration. They also donned their suits, without helmets and gloves, to use the foot restraints built for the suits during reentry. Since this mission, space suits have not been worn for reentry but have been donned for critical mission phases such as separation and docking and, of course, lunar surface activity. Pressurization of space suits which serve as a backup to the cabin pressure has never been necessary except during planned EVAs.

Radiation

The radiation environment of space has been sampled by numerous probes and has been calculated at length. The Gemini flights generally did not reach an altitude involving the Van Allen belts, but they did pass through the South Atlantic anomaly. The onboard radiation measuring system and the personal dosimeters on the crewmembers confirmed that the environment at that point is at the lower end of the calculated range. In a 60 nautical mile orbit, crews received approximately 15 millirads per 24 hours in the Gemini program. Table D-6 shows radiation doses on Gemini missions.

TABLE D-6: Radiation Doses on Gemini Missions

Mission	Duration, day:hr:min	Mean cumulative dose, mrad	
		Command pilot	Pilot
III	0:04:52	<20	42±15
IV	4:00:56	42±4.5	50±4.5
V	7:22:56	182±18.5	170±17
VI-A	1:01:53	25±2	23±2
VIII	13:18:35	155±9	170±10
VIII	0:10:41	<10	10
IX-A	3:01:04	17±1	22±1
X	2:22:46	670±6	765±10
XI	2:23:17	29±1	26±1
XII	3:22:37	<20	<20

Apollo 8 was first to leave earth orbit and traverse the Van Allen belts, during translunar and transearth coasts. At these times, the crewmen of Apollo 8 and other Apollo lunar missions have been exposed to direct galactic radiation and to solar flare particles on occasion. The solar flare network can help predict solar events. Additionally, on-board instrumentation (see Table D-7) can measure the radiation. The shielding provided by the Command Module gave assurance that doses received would be tolerated by the crew even under the most severe conditions anticipated. Doses actually received have been small. Apollo 14 doses were the largest observed on any Apollo mission; however, they were well below the threshold of detectable medical effects.

TABLE D-7: Radiation Instrumentation on Apollo Missions

Instrument	Measurement	Location
Nuclear particle detection system (NPDS)	Alpha-proton spectrometer (4 channels proton, 15 to 150 MeV; 3 channels alpha, 40 to 300 MeV); telemetered	Service module
Van Allen belt dosimeter	Skin and depth dose rates; telemetered	CM
Radiation survey meter	Portable, hand-held ratemeter; 4 linear ranges, 0 to 0.1 to 0 to 100 rad/hr; visual readout	CM (portable)
Personal radiation dosimeter	1/crewman; accumulated radiation dose; 0.01 to 1000 rad; visual readout	Suit
Passive radiation dosimeter	4/crewman; emulsion/thermoluminescent dosimeters; postflight analysis	Constant-wear garment

Gravity and Weightlessness

In the space environment, gravity was expected to produce effects because of its increase at the time of launch and reentry and its absence in the state of weightlessness during the actual flight. Ground based centrifuge runs provided ample assurance that anticipated loads at launch and reentry were well within man's tolerance. This information was confirmed on flights with two 7 g peaks at launch and gravity varying from 4 to 8.2 g at reentry in the Gemini program. There was concern about a decreased g-tolerance at the time of reentry following weightless flight, but no evidence was observed. The Gemini IV crew sustained an 8.2 g peak without adverse effects following four days of weightlessness. For the Apollo launches the g-profiles were of less magnitude than those experienced with the Gemini system. Apollo 7 (earth orbital) launch and reentry levels were both 3.3 g. Launch level for Apollo 8 was 3.86 g, and, since the entry was from a lunar trajectory, the g-load was higher -- 6.8 g.

Prior to actual manned spaceflight, weightlessness was produced for only brief periods in parabolic flight in aircraft and partially simulated on the ground by water immersion and bed rest.

In Gemini and Apollo missions, crews have reported that after attaining weightlessness, they have a feeling of fullness in the head. This has lasted for varying periods of time lasting up to three days. The crews also report

an awarness of the weightlessness of clothes and other objects.

Since there is minimal effort involved in moving about in the spacecraft, less work is required for a task than is required in one-g. Overall, the crews have adapted well to the weightless environment, finding it pleasant and helpful in accomplishing inflight activities.

Although flight experience has now provided evidence about the effect of the weightless environment on various body systems, it is impossible to state definitely that the effects observed are those of weightlessness only, since obviously they result from a complex of factors in the spaceflight situation.

Sleep, Work/Rest Cycles

It was predicted that the space environment would produce both sleepiness and sleeplessness. In the Mercury and Gemini spacecraft, crewmen were fixed in place in the flight couches in which only slight movement was possible. Difficulty in obtaining satisfactory sleep was observed, particularly on the first two nights inflight. There was also a tendency to wakefulness on the part of the command pilot who continued to feel the responsibility to check spacecraft status at intervals. It appeared that the amount of sleep obtained was less than that obtained in normal situations on the ground. There was normal dream activity. In the Gemini series the electroencephalograph was used on one astronaut in the 14-day flight producing a total of 54 hours and 53 minutes of interpretable data. The depth of sleep ranged from stage 1 to stage 4, as in ground based data. In some flights, major interference with work/rest cycles was avoided by having the sleep and meal periods coincide with sleep and meal periods at Cape Kennedy regardless of the mission plan. This worked out very well.

Sleep in the weightless state was a continuing problem on the Apollo missions. The crews have required approximately 3 nights to adapt to sleep. They continue to desire contact with some object and have tried to wrap an arm or a leg around something, even when they are floating free in the sleep station. All the sleep periods have been attenuated.

The requirement for one crewman to be on watch at all times during the early Apollo missions (requiring activity by all three crewmen) were particularly difficult factors in the flight planning. The circadian rhythms of the entire crew were disrupted. They were sleeping at odd times, and the effects of weightlessness combined with the noise of the other crewmen communicating with the ground stations produced an unsatisfactory situation. The crews all became fatigued; this was most evident on the Apollo 8 mission. On this mission the crewmen lacked adequate rest prior to the 24-hour lunar orbit period during which they obtained no rest at all. Fatigue interfered with their ability to perform. On the Apollo 9 flight, all three crewmen slept at the same time since responsible officials had sufficient confidence in the spacecraft systems. Sleep was much improved but again the sleep periods in the early portions of the mission were difficult and of much shorter duration than on the ground. Late in the flight, after the crew

had accommodated to the weightless environment and the activity pattern, they had long sleep periods up to 8 and 9 hours.

The Apollo 13 crew slept well until the oxygen tank incident -- approximately 5 hours prior to the third sleep period. After the decision to abort the mission, the three crewmen obtained only 11, 12, and 19 total hours of sleep during the 82-hour period prior to splashdown in the too-cool, powered-down spacecraft.

The Apollo 14 lunar module crewmen received little, if any, sleep between their two EVA periods. This insomnia was believed to be caused by the lack of an adequate head rest, pressure suit discomfort, and the 7-degree starboard list of the Lunar Module caused by the lunar terrain. Visual reassurance through the window to see that the LM was not starting to tip over was obtained several times during the sleep period by both crewmen.

During the Apollo 15 mission operational problems aboard the Lunar Module after landing necessitated lengthening the work days and reducing the planned sleep periods. This, coupled with a significant shift of the LM crewmen's circadian rhythms, caused a significant fatigue level in the crewmen, who operated on their physiological reserves until returning to the Command Module.

An inflight workday of 12 hours, with a sleep period of 8 hours and a 4-hour leisure period, seems optimum.

Nutrition

Among concerns about weightlessness were the potential difficulties in eating and drinking. Difficulties with amoeboid masses of water had been demonstrated in zero-g aircraft flight, along with numerous other unsatisfactory experiences with liquid and semisolid food. Also, anorexia, nausea, vague gastrointestinal disturbances, urinary retention, and diuresis were predicted. In actual experience, the difficulties of eating and drinking have been easily handled by proper packaging of food and by the use of a water gun which meters the water directly into the mouth or into the food packet. Freeze-dehydrated foods have been used with water being added directly to the containers. In the Apollo flights hot water was available and thus the palatability of the food has markedly increased. The bite-size foods are coated to avoid crumbling. The dietary intake in calories has varied greatly among individuals.

Although there was variation in the total calories provided in the menu per flight, it has averaged around 2500 calories per man per day. The lowest caloric intake was during the 8-day Gemini flight when the crewmen ingested only 915 and 1075 calories per day, respectively. The diet consisted of approximately 17% protein, 32% fat, and 51% carbohydrates.

There have been complaints about the food, which should be expected in any flight program. Crewmen were allowed to choose their menu, but it was difficult to provide enough variability for the longer flights. The rehydratable foods appear to be preferred over the bite size foods. In the

Apollo flights some moisture foods specially packaged and eaten with a spoon were utilized. These hydrated foods were well accepted by the crews.

Cardiac arrythmias were noted in EKGs of two Apollo 15 crewmen -- the two who had made the lunar landing. Postflight checks revealed that each had lost 15% of his normal potassium. This low level was suspected as a possible cause of the erratic heartbeats. To counteract this problem, which had not appeared on earlier Apollo missions, the diets of the Apollo 16 crew contained an increased amount of potassium. As the Apollo 16 mission neared its end, only three erratic heartbeats from the crew had been observed. This number was not considered abnormal.

Early spacecraft water systems were subject to cross connections with the waste water and urine systems through a series of valves. It was demonstrated that bacteria from the waste water could enter the potable tank; therefore, systems for keeping the water potable were designed. In the Apollo Command Module, a system of chlorination was used while in the Lunar Module; iodine was the choice. Bacteria-free water was maintained by these methods, but the taste continued to be a problem of crew concern. In addition the fuel cell source in the Command Module in the Apollo 9 mission resulted in the water being filled with hydrogen bubbles which were a source of annoyance to the crew. On the Apollo 11 and 12 flights water/gas separators satisfactorily removed this gas.

Intravehicular Activity

Early high metabolic loading during Gemini EVAs caused concern about the probable metabolic costs of intravehicular activity (IVA) in the larger Apollo spacecraft where such activity was possible for the first time. Actual experience, however, proved that little effort was demanded for activity within the spacecraft environment. Large masses were moved about freely with minimal effort, and the crews utilized the intravehicular environment as an asset in conducting the flight plan activity. No undue increases in heart rate were noted as a result of this activity.

Physiological Considerations

SKIN. Only minimum skin reactions surrounding sensor sites have been noted and these cleared rapidly postflight. There have been a few small inclusion cysts on occasion. On several missions there was an increase in dandruff and some exacerbation of seborrheic dermatitis involving the face. Attempts to prevent this included the use of medicated shampoos and lotions preflight. Despite the fact that inflight bathing was impossible, there was no real skin infection or breakdown. Some drying of the skin with a generalized flaking was noted following missions of 8 and 11 days duration.

On Apollo 15, one crewman had hemorrhages under several fingernails. The hemorrhages resulted from an insufficient pressure-suit arm length, which forced the fingertips too far into the EV gloves during space suit operations.

The space suit fit had been adjusted to the crewman's preference to increase his sensitivity of touch.

BODY WEIGHT. A postflight weight loss has been noted on every mission but has not increased with mission duration. The weight losses varied widely from 2-1/2 to 14 pounds (Table D-8). It appeared that most of the weight loss was replaced with fluid intake within the first few hours postflight in the Gemini program, but this has not been the case in the Apollo missions, where only a partial replacement of the weight within the 24 hour period postflight has been observed.

EYE, EAR, NOSE, AND THROAT. There have been two inflight incidents of rather severe eye irritation, one of which resulted from exposure to lithium hydroxide in the suit circuit and the other of unknown origin. Conjunctival injection was evident on most postflight examinations as a result of exposure to the oxygen environment. Nasal stuffiness and hoarseness were observed inflight, due to the oxygen environment. This was treated with antihistamines and decongestants or with a nasal emollient, generally with good results. There have been a few incidents of postflight serous otitis of a mild degree.

RESPIRATORY SYSTEM. Preflight and postflight x-rays failed to reveal any atelectasis. Pulmonary function studies were consistently normal pre- and postflight. There have been no specific difficulties or symptomatology involving the respiratory system.

CARDIOVASCULAR SYSTEM. It had been predicted that arrhythmias might occur during acceleration and deceleration and that bradycardia, with perhaps arrhythmia, also might develop during the midportions of the flight. It was also predicted that there might be redistribution of blood volume and difficulty with adequate venous return upon reentry into the gravity environment after being weightless. Fainting or loss of consciousness was anticipated. In actual manned flight the cardiovascular system did show some early changes. A summary of the cardiac rates at launch and reentry for Gemini and Apollo is presented in Table D-9.

Heart rates varied with the sleep cycle and were elevated consistently at launch and reentry. The midportions of the flight were characterized by a lower resting heart rate than that observed preflight. The postflight resting heart rate was elevated as much as 45 beats per minute for 24-50 hours postflight. No significant arrhythmias were observed and only rare premature auricular and ventricular contractions were noted. There were no significant changes in the duration of specific segments of the electrocardiogram. Inflight blood pressures obtained through 14 days of spaceflight revealed no significant variations from normal. Fluctuations in the duration of electromechanical systole were observed, but these correlated closely with changes in the heart rate. The electromechanical delay, measured from the onset of the QRS complex to the onset of the first heart sound, remained stable throughout the flight. Slightly shorter values were observed during the periods of highest heart rate, such as lift-off, reentry, and EVA. Exercise response to a standard 30 second bungee pull did not vary throughout 14 days of spaceflight.

TABLE D-8: Flight Crew Weight Loss to Nearest Half Pound

Gemini Mission	Command Pilot	Pilot
	lb	lb
III	3.0	3.5
IV	4.5	8.5
V	7.5	8.5
VIA	2.5	8.0
VII	10.0	6.0
VIII	-*	-*
IXA	5.5	13.5
X	3.0	3.0
XI	2.5	0
XII	6.5	7.0

Apollo Mission	Commander	Command Module Pilot	Lunar Module Pilot
	lb	lb	lb
7	6.5	10.0	8.0
8	9.0	9.0	4.0
9	5.5	6.0	6.0
10	2.0	6.0	9.5
11	7.5	7.0	1.5
12	4.5	7.5	12.5
13	14.0	11.0	6.5
14	0	10.0	0
15	2.8	3.0	5.5
16	-*	-*	-*

*Data not available.

TABLE D-9: Peak Heart Rates during Launch and Reentry for Gemini and Apollo

Program	Mission	Crewman*	Peak Rates During Launch	Peak Rates During Reentry
			Beats/Min	Beats/Min
Gemini	III	CP	152	165
		P	120	130
	IV	CP	148	140
		P	128	125
	V	CP	148	170
		P	155	178
	VIA	CP	125	125
		P	150	140
	VII	CP	152	180
		P	125	134
	VII	CP	138	130
		P	120	90
	IXA	CP	142	160
		P	120	126
	X	CP	120	110
		P	125	90
	XI	CP	166	120
		P	154	117
	XII	CP	136	132
		P	110	137
Apollo	7	CMDR	94	--**
		CMP	--**	--
		LMP	--	--
	8	CMDR	118	92
		CMP	--	--
		LMP	--	--

TABLE D-9: Peak Heart Rates during Launch and Reentry during Gemini and Apollo (Cont'd.)

Program	Mission	Crewman	Peak Rates	
			During Launch	During Reentry
			Beats/Min	Beats/Min
Apollo	9	CMDR	145	110
		CMP	135	82
		LMP	95	82
	10	CMDR	128	109
		CMP	117	110
		LMP	93	112
	11	CMDR	114	99
		CMP	100	95
		LMP	88	101
	12	CMDR	130	101
		CMP	115	98
		LMP	123	100
	13	CMDR	119	NO DATA
		CMP	110	NO DATA
		LMP	111	NO DATA
	14	CMDR	--	
		CMP	--	
		LMP	--	
	15	CMDR	--	
		CMP	--	
		LMP	--	
	16	CMDR	--	
		CMP	--	
		LMP	--	

* CP - Command Pilot
CMDR - Commander
LMP - Lunar Module Pilot
CMP - Command Module Pilot
P - Pilot

** Data not available

Although orthostatism was observed in the last two Mercury flights, it was detectable in the later Gemini flight series only when provoked by exposure of the crew to a passive tilt at 70° for 15 minutes or, in Apollo, to lower body negative pressure (LBNP) for 5 minutes at 30, 40, and 50 mm Hg negative pressure. Three preflight baseline tilts or LBNP procedures served as baselines for comparison with the postflight measurements, and postflight measurements were repeated until the results were within the range of the normal preflight values. Immediately postflight in the tilts, an increased heart rate, reduced pulse pressure, and an increased leg volume were noted. Immediately postflight, LBNP determinations showed significant increases in heart rate and decreases in blood pressure. When presyncopal symptoms in the tilt and LBNP were noted, procedures were stopped short of completion of the first postflight evaluation. The finding in both tilts and LBNP returned to normal within 50 hours postflight, regardless of flight duration, with the exception of the Apollo 15 mission, where return to baseline required approximately one week. Typical heart rate response to the first postflight LBNP is shown in Figure D-1, which also contains the 70° tilt results of the same crewman from a 14-day Gemini flight. The magnitude of these changes was greatest following the 8-day Gemini mission and the findings less severe in the 14-day mission. This was due to many factors including exercise, diet, and the removal of the flight suits in the 14-day mission. The findings in the Apollo series were of less magnitude than those in the Gemini series but greater than anticipated in view of the opportunity for movement and exercise in the larger Apollo cabin. It is evident that there is some effect upon the cardiovascular system during space-

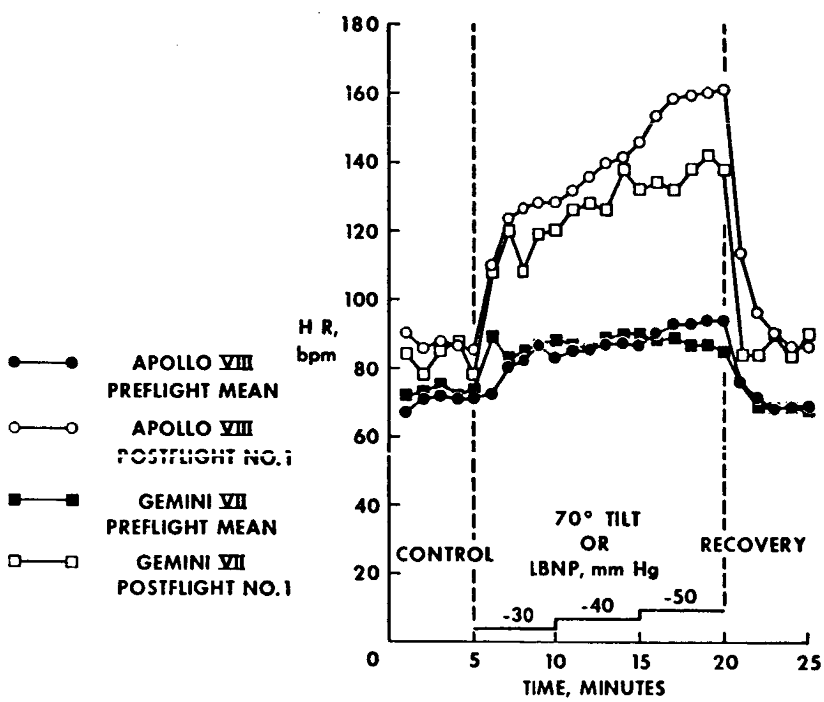


FIGURE D-1: Postflight Orthostatism Induced by Passive Tilt or Body Negative Pressure

flight which results in an increased pulse rate response to the stresses, increased lability of blood pressure, and decreased pulse pressure.

BLOOD. A decrease and redistribution of blood volume was predicted, principally on the basis of bedrest data. The crewmen consistently reported a feeling of fullness of the head during the early portions of the missions, which may be the result of a redistribution of blood volume. On each of the long duration missions and in the Apollo series, plasma volume and red cell mass were measured by radioisotope techniques. Red blood cell mass losses were 5% in the 4-day mission and 20% in the 8- and 14-day missions, as shown graphically, along with the findings in the Apollo series, in Figure D-2. The Apollo spacecraft were launched with an approximately 60% oxygen and 40% nitrogen environment, which was altered inflight by replacing the leak rate with 100% oxygen, although the oxygen percentage reached only 93%. The red cell mass change in the Apollo series ranged from 9% in one crewman to a low increase of only 2.3% in another crewman on the 7-day Apollo 8 mission.

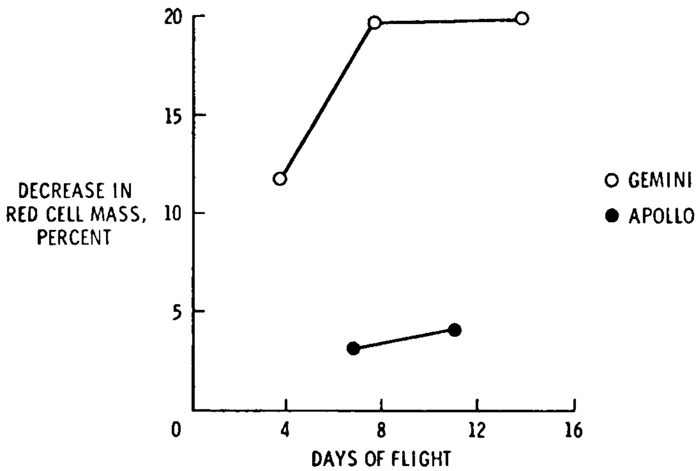


FIGURE D-2: Red Cell Mass Change

Essentially, in Apollo, there was no change in red cell mass unless the cabin atmosphere was 100% oxygen. It is believed that the atmosphere was the significant causative factor in the production of red cell mass decreases observed in the Gemini series. These data were confirmed when no decrease was found after a chamber study conducted with the Apollo spacecraft. On the other hand, there was loss of red cell mass in the Apollo series when the crew was subjected to 7 days of 100% oxygen following decompression of the cabin for EVA. Thus, there were no significant changes in plasma volume nor in red cell survival in the Apollo series in contrast to those observed in the Gemini series.

Routine hematology showed a significant and absolute neutrophilia in the immediate postflight count. Although these counts reached 28,000, they were more often in the 10,000-15,000 range and returned to normal within 24 hours postflight. It is believed that this finding represents a stress response.

MUSCULOSKELETAL SYSTEM. There were predictions of demineralization of bone and the development of muscular incoordination and atrophy following exposure to the spaceflight environment. Manned spaceflight thus far has given no indication of muscular incoordination or atrophy, but there has been some bone demineralization as evidenced by x-ray densitometry studies of the feet and hands. Decreased density was observed in both of these areas in the Gemini series. These changes, however, were observed in differing flight situations, including varying dietary intakes of calcium. In contrast with the Gemini series, the Apollo flight crews had uniform dietary intakes and were able to move about and exercise in the larger spacecraft. Minimal loss of bone density was observed, as is noted in Figure D-3.

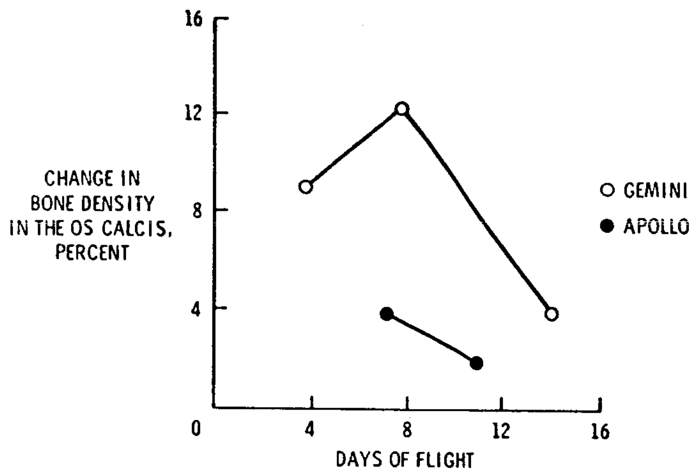


FIGURE D-3: Bone Density Change

There was a rapid change in bone density depending upon the activity level during the 30-day period preflight and the 21-day period postflight. The bone density returned to normal within a few days postflight.

A detailed calcium balance study on the 14-day flight verified the negative balance trends demonstrated thus far. There was evidence of loss of nitrogen and, thus, muscle mass. None of these changes, however, could be considered to have reached a dangerous level.

EXERCISE CAPACITY. The Gemini series utilized bicycle ergometry with a constantly increasing workload to a peak performance of the crewman, usually indicated by a heart rate of 180. This method was useful not only in measuring exercise capacity but also in permitting calibration of the individual by establishing a Btu energy output for a given heart rate. A graph of this function was of great assistance in the real-time monitoring of EVA. It was observed, particularly following the 14-day Gemini flight, that there was a decrease in exercise capacity. In the Apollo series, the test was modified by utilizing a bicycle ergometer programmed to respond to the heart rate of the crewman. The workload necessary to produce heart rates of 120, 140, and 160 was maintained for 3 minutes each. In addition to

two determinations by the above method, a maximum capacity determination was also made preflight and postflight.

The Apollo crewmen showed a significant reduction in work performed at the specified heart rates. This reduction varied with the subject, but the average for one flight crew showed a 70% reduction at 120 heart rate, 40% reduction at 140 heart rate, and a 20% reduction at 160 heart rate. Other crews did not show this rate-related decrease but had a general decrease in capacity at all heart rates. These values in all instances returned to the preflight normal within 24 hours postflight.

Supporting data showed that the decrements in work performance were not a result of changes in ventilatory function or of the ability of subjects to obtain oxygen from the atmosphere. All pulmonary function studies were within normal limits. These findings were of particular interest in planning for lunar surface activities and other strenuous inflight events.

IMMUNOLOGIC AND BIOCHEMICAL OBSERVATIONS. Immunology studies in the Apollo series involved a survey of the serum protein fractions, lymphocyte response, and RNA and DNA synthesis. No significant changes were observed in any of these determinations in the pre- and postflight situations. Postflight changes in the C reactive protein levels were noted in certain crewmen, consistent with their inflight diseases.

Urine samples were obtained inflight on two occasions; serum samples were obtained only pre- and postflight. Inflight urine specimens revealed a slight reduction in the output of sodium and some increase in aldosterone excretion. Potassium excretion was also reduced inflight and postflight. The 17-hydroxycorticosteroid values were depressed during flight. The Apollo series pre- and postflight determinations showed a marked increase in urinary values and a decrease in plasma free hydrocortisone levels (compound F) in the immediate postflight samples. These returned to baseline values by 6 days postflight.

In Apollo flights, a consistent postflight hyperglycemia was noted. This was a possible result of an increased output of catocholamines and steroids secondary to the "stress" of reentry. Serum cholesterol and uric acid levels were decreased from the preflight levels, probably due to the altered diet of the crewmembers.

Measurements of bone mineral status have shown some increase in postflight serum bound hydroxyproline and the excretion of larger quantities of calcium late in the flight. These changes are consistent with the change in bone structure.

SPECIAL SENSES AND THE CENTRAL NERVOUS SYSTEM. There has been no evidence of central nervous system dysfunction or abnormal psychologic response such as the breakoff phenomenon as a result of being separated from earth. Inflight crew relationships have been good, and there has been no evidence of undue psychologic stress.

There had been various predictions regarding visual capabilities and vestibular functions. It was suggested, for example, that there would be a reduction in visual acuity. It was widely accepted that disorientation and motion sickness might ensue as a result of weightless flight. Numerous visual observations were made involving both objects inflight and on the ground. In many cases it was possible to check the position of the objects and confirm such sightings. In addition, inflight vision tests, onboard the spacecraft and with the use of specially constructed targets on the ground, showed no decrement in visual acuity throughout 14 days of spaceflight.

Throughout Mercury, Gemini, and the first manned Apollo flight, there was no evidence of disorientation or motion sickness in flight, even though the crews participated in tests involving violent head movements in the spacecraft and movement in the extravehicular situations. On several of the later Apollo flights, however, certain of the crew developed a stomach awareness and nausea early in the flight. This discomfort was associated with movement about the spacecraft early in weightless flight and with the large volume of the spacecraft which allowed for movement. The crew accommodated to this movement over a period of hours or a few days.

GASTROINTESTINAL SYSTEM. With the exception of the inflight illnesses, the gastrointestinal tract function was normal on all missions. There is no evidence to indicate other than normal gastrointestinal motility, and there appear to be no excess nutrient losses during flight. The crews were placed on low residue diets preflight and prepared for the mission by administration of an oral laxative 2 days before launch. This was an effective means of preparing the bowel and reducing the number of inflight defecations.

GENITOURINARY SYSTEMS. There were no difficulties involving the genital system. Urination occurred normally both inflight and postflight and there was no evidence of renal calculi.

MICROBIOLOGY. Verology and bacteriology/mycology studies were conducted on early Apollo missions to provide a baseline for the lunar missions and their quarantine period. The only viral agents isolated were those in all three Apollo 9 crewmen. This virus was the agent responsible for the preflight upper respiratory disease which caused a 3-day postponement of the launch date.

There were transfers of microorganisms from man to man within the isolated cabin environment. There was enhancement of the growth of gram-positive organisms such as staphylococcus aureus and B-hemolytic streptococci and, in addition, a reduction of microorganisms in the anaerobic class. It appears, therefore, that the space environment may produce some simplification of microflora which enable opportunist microorganisms to dominate.

On one of the lunar missions, staphylococcus aureus was noted in two skin site samples from the crew preflight. It was cultured from most skin sites on all crewmen postflight and from the spacecraft. It was also

implicated in pustules about the sensor sites on the crew's chests, in two postflight sinusitis cases, and in a wound infection.

DRUGS. In the early planning for spaceflight, it was decided that a drug kit should be available for inflight prescriptions. The kit was modified from the small tablet container in Mercury to the larger, more complete medical kit in the Apollo program. Medications in the kit were selected after careful review of the possible medical difficulties arising inflight. They were modified for longer missions to provide the capability for treating three crewmen for several days before they could return to earth. Each crewman was carefully checked for his reaction to each of the drugs carried in the kit. All drugs were administered preflight and their reactions charted. With the exception of aspirin, medications in the kit were prescribed by the Flight Surgeon from the ground Control Center. The contents of the kit are listed in Table D-10.

TABLE D-10: Apollo Medical Kit Contents
Injector-pain, Demerol 100-mg
Injector-motion sickness, Marezine 45-mg
Capsule-pain, Darvon 65-mg
Tablet-stimulant, Dexedrine 5-mg
Tablet-motion sickness, Marezine 50-mg
Tablet-diarrhea, lomotil 2.5-mg with 0.025 atropine
Tablet-decongestant, actifed
Tablet-analgesic, aspirin
Capsules-antibiotic, ampicillin 250-mg
Tablets-antibiotic, Achromycin 250-mg
Capsules-sleep, Seconal 100-mg
Capsules-sleep, Seconal 50-mg
Capsules-antihistamine, Benadryl 100-mg
Tablets-analgesic, Tylenol
Liquid-nasal emollient, Ponaris
Spray-Nasal, Afrin
Ointment-antibiotic, Neosporin
Cream-skin, J&J First Aid Cream
Bandage compress
Band Aids
Drops-eye, methylcellulose
Oral thermometer
Cuffs urine device
pH paper roll
Sternal electrode harness
Axillary electrode harness
Electrode paste

Experience with the sleep problem on Apollo 7 and concern for the more complicated missions leading to lunar landing led to the addition of Seconal to the drug kit. This addition of 100 mg of Seconal was carefully considered, because it was contrary to the earlier medical position concerning the use of drugs inflight. The crewmen were pretested by awakening them 1 hour after administration of the Seconal and requiring them to perform some demanding task satisfactorily. In all instances this was possible. Seconal was used successfully on several Apollo missions. Aspirin was used inflight for occasional mild headache and for relief of muscular discomfort prior to sleep. Dextroamphetamine sulfate was taken on several occasions by fatigued crewmen prior to reentry. An antihistamine-decongestant combination to relieve nasal congestion and for the clearing of the ears was used prior to reentry. The antimotion sickness medication taken prior to reentry to prevent motion sickness, resulting from the motion of the spacecraft in the water after landing, was also taken inflight for stomach awareness and nausea. Marezine was used early in the program, but after Apollo 10, a combination of Dexedrine and Scopolamine was used. An inhibitor of gastrointestinal propulsion was prescribed to prevent unwanted defecation inflight. The nasal emollient was used a number of times to preclude drying of the nose. The nasal decongestant spray and the eye drops were also used frequently. No difficulty was experienced in the use of these medications inflight and they produced the desired effects. No injections were used inflight.

INFLIGHT DISEASE. The development of infectious disease inflight as a result of preflight exposure and the lack of symptoms or signs which could be detected in a preflight examination were foreseen. Accordingly, a modified quarantine or isolation was attempted prior to the long duration flight in the Gemini series. Total quarantine of the crews for a period of time before flight was impractical, however, because the immediate preflight period was demanding and required crew participation. Efforts were therefore directed at screening the contacts to reduce the crew's exposure to infections, particularly of the upper respiratory and gastrointestinal type. Fortunately, in the Gemini series there were no inflight illnesses. There were a number of short-lived, flu-like syndromes, one exposure to mumps, and one instance of B-hemolytic streptococcal pharyngitis which occurred preflight. Each situation was handled without effect on the scheduled launch, and no inflight illness or complication was noted.

The situation with the Apollo flights was markedly different. Four days prior to the launch of Apollo 7, one of the crew developed loss of appetite and symptoms of an upper respiratory illness. He was treated with antihistamines, a decongestant, and an antibiotic, as the backup crew had been found to have streptococcal pharyngitis within the previous week. Later that day the second crewman complained of similar symptoms and was similarly treated. Treatment was carried through until the morning of the flight. On the launch date none of the crew demonstrated manifestation of illness or evidence of prodromal symptoms. Approximately 15 hours after liftoff, however, the third crewman reported onset of what he termed a "bad head cold". He was treated with an antihistamine and decongestant combination with some relief. Twenty-four hours later the first and second crewmen experienced identical symptoms. These symptoms continued for the bulk of the flight period in all three crewmen.

Predictions about the symptoms of upper respiratory disease were borne out when the crew reported a feeling of nasal and sinus fullness which could be cleared only on forceful blowing; there was no postnasal drip or nasal drainage in the weightless state and no coughing. As there was much concern by the crew about possible ear blockage on reentry, they were well premedicated with the antihistamine decongestant combination for 24 hours before reentry. Only one of the crewmen developed a barotitis upon reentry.

Prior to the Apollo 8 mission, a large number of cases of acute viral gastroenteritis lasting for 24 hours occurred in the Cape Kennedy area. Eighteen hours after launch, the commander of this mission complained of nausea which terminated in vomiting on two occasions. This illness was short-lived and required no treatment, but it did cause concern about its possible spread to the other crewmen.

In the immediate preflight period leading to the Apollo 9 launch, all three crewmen developed an upper respiratory illness best characterized as the common cold, involving the ear, nose, and throat. They were treated with an antihistamine-decongestant combination and rest, but their condition required postponement of the launch for three days. This was the first manned launch ever delayed for medical reasons. There was concern about the irritation of this condition inflight or a relapse of the condition in the oxygen environment; however, the only illness noted inflight on this mission was a 24 hour gastrointestinal upset with nausea and vomiting on two occasions by one of the crewmen. This was treated with cyclizine (Marezine) and diphenoxylate hydrochloride with atropine (Lomotil).

Nine days before the Apollo 13 launch, one of the prime crewmen was exposed to German measles. Since laboratory tests indicated that he was not immune to this highly communicable disease, he was replaced by his backup counterpart. Also on the Apollo 13 mission, a retrograde urinary tract infection developed in one crewman due to constant wear of the in-suit urine device and reduced water intake. The organism was Pseudomonas aeruginosa, and its eradication required prolonged postflight treatment.

There is little doubt that these inflight illnesses had some effect on the inflight activities during these missions. In addition to the preflight and flight incidents, crewmen also had postflight illnesses. These consisted of the respiratory flu-like symptoms, some influenza of the Hong Kong strain, and gastroenteritis. This marked occurrence of illness in the Apollo Program led to a change in the preventive medicine plan to include a modified isolation for 21 days preflight. It would be difficult if not impossible to provide a more extensive plan for isolation and still fly the mission.

The experience so far suggests that the crew's resistance was lowered in the preflight period. A probable factor in the lowering of resistance was fatigue from the numerous demands upon the crew during this training period. The complexity of missions required much training and briefing time. Careful attention was given to preclude the development of this fatigue and the lowering of resistance during this critical period. This was equally true in the postflight period, when there was also a great deal of activity. The crew was fatigued from the mission, and there was a requirement for early postflight

debriefings. These were ordinarily followed by a number of public affairs activities exposing the crew to large numbers of people in various parts of the country. Conditions such as these make postflight disease prevention difficult. A problem complicating the treatment of inflight illness was the difficulty of communications between doctor and patient. All communications between the spacecraft and the control center were open communications and readily available to the press on a real-time basis. Limited private communication transmissions, established for the illnesses in two of the Apollo missions, were of great assistance.

Conclusion

The medical profession concerned with manned spaceflight has had an opportunity to observe men exposed to the spacecraft environment in both a confined and relatively unconfined state and also in both intravehicular and extravehicular activities for a number of hours. It appears that the body systems attempt to accommodate to the less demanding weightless environment and that they do so with changes which have, to date, produced no particular difficulties inflight. At the conclusion of flight, however, the body again must reaccommodate to the one gravity environment, particularly the cardiovascular and musculoskeletal systems. None of these changes, however, has been long-lived, and the body has reaccommodated to a one-g environment within a few days postflight. At present, none of these demonstrated accommodations is considered limiting so far as future manned spaceflight is concerned. Further investigation, as discussed below, is indicated for very long-duration flights.

SKYLAB BIOMEDICAL EXPERIMENTS

The significance of the Skylab Program is its dedication to scientific exploration. Although the study of man and his responses to the space environment is only one of four major objectives -- the other three being the study of the earth, of the sun, and of technology -- it is the focus of the discussion in this section.

As shown from Mercury, Gemini, and Apollo missions, the responses of man to the spaceflight environment have followed predictable adaptive processes. Significant medical results from Gemini and Apollo missions are given in Table D-11. In planning for future longer duration flights, it becomes imperative, before man is committed to these flights, to understand how much and for how long these observed physiological changes persist, and to determine whether these changes will allow man to spend months or years in space and then safely return to the earth and readapt to the one gravity environment.

Answers to these questions can be obtained only through a careful, quantitative study of these adaptive processes. This study is the objective of the Skylab space medical program.

The biomedical experiments scheduled for Skylab reflect observations made during the earlier flights (see Table D-11). Priority for selecting these experiments also reflects this flight experience. The experiments, directed to six major areas of body functioning, will be extensions of studies into the phenomena and mechanism of some of the previous findings and will also

TABLE D-11: Significant Medical Results--Gemini and Apollo

GEMINI
MODERATE LOSS OF RED CELL MASS
MODERATE CARDIOVASCULAR DECONDITIONING
MODERATE LOSS OF EXERCISE CAPACITY
MINIMAL LOSS OF BONE DENSITY
MINIMAL LOSS OF CALCIUM AND MUSCLE NITROGEN
MODERATE BODY WEIGHT LOSS
HIGH METABOLIC EXPENDITURE DURING EVA
APOLLO
NO LOSS OF RED CELL MASS
MODERATE CARDIOVASCULAR DECONDITIONING
MODERATE LOSS OF EXERCISE CAPACITY
MINIMAL LOSS OF BONE DENSITY
MODERATE BODY WEIGHT LOSS
LOW METABOLIC EXPENDITURE DURING LUNAR EVA
INFLIGHT MOTION SICKNESS

introduce new measurement to be accomplished for the first time in manned spaceflight. Table D-12 details the six major areas of interest of the Skylab experiments. A discussion of each of these areas follows.

M070 - Nutritional and Musculoskeletal Functions

As noted earlier, there have been consistent losses recorded on the musculoskeletal system during pre- and postflight studies. Questions have been raised as to whether these changes are related to weightlessness, nutritional intake, or lack of musculoskeletal functioning, due either to reduced demand upon it for work or to reduced stimulation of the musculoskeletal system in weightlessness. There has also been a persistent and rapid loss of body fluid after the onset of weightlessness. Three to eight percent of the body weight loss has occurred within 12 to 24 hours of weightlessness. The loss of fluids appeared not to progress beyond this point unless there was another 8% of body weight loss caused by sweat due to in-

adequate thermal control or inadequate fluid intake. Electrolyte loss was also expected, since the fluid loss was acute and little time for electrolyte saving could be activated.

A series of experiments have been chosen to study this area: total intake and output will be performed through the use of a carefully controlled diet which will provide 100 ± 10 grams protein, 800 ± 16 milligrams calcium, 1600 ± 160 milligrams phosphorus, 350 ± 100 milligrams magnesium, and 6000 ± 500 milligrams sodium, within the first 2000 calorie/day. Supplemental carbohydrates are available to bring the total diet up to the individual astronaut's caloric demands, with a maximum limit of 2800 calories/man/day intake. Fluid intake will be metered and recorded. The mass of food not eaten will be measured so accurate records may be obtained. The daily urine volume of each astronaut will be measured and a representative sample of 125 milliliters will be collected, frozen and returned to earth for postflight analysis. The concentration of inorganic and organic constituents will be determined from these urine samples. The excretion of the elements provided in the diet will be obtained. Sweat will not be measured; however, the temperature of the workshop will be held within an established comfort zone and only short periods exceeding insensible sweating are expected. A photon absorption technique will be employed pre- and postflight on selected bones, weight- and nonweight-bearing, to correlate bone density changes with the nutritional and biochemical studies.

As noted earlier, there have been some detectable orthostatic changes observed after each flight of over one day in length. The degree or severity of the changes has varied widely. For some of the more recent crewmen who landed on the moon, it would appear that the lunar gravity or the workload on the moon or the combination of both factors may provide some protection. In addition, it is recognized that other factors such as fluid balance and electrolyte balance could influence the cardiovascular system picture, and these areas have also been altered on flights to date. The M070 series discussed above (Figure D-4) will give data on fluid, electrolytes and energy intake. The M170 series, discussed later, will address the metabolic balance and energy costs of work and thus provide data on other factors influencing the cardiovascular system.

M090 - Cardiovascular Function

The tests of the cardiovascular system will add an inflight phase to many of the studies previously done only before and after flights (Figure D-5). Provocative testing will be used. The use of the Lower Body Negative Pressure (LBNP) apparatus will replace the tilt table, and it can be operated in weightless flight. The LBNP will enclose the body from the diaphram downward. Testing will include step increases in differential pressure of 20-25 mm Hg, 30-35 mm Hg and 40-45 mm Hg. Heart rate, blood pressure and lower limb phethysmography will be performed as a means of monitoring the conditions of the crewmen. Vectorcardiography will also be recorded during this stress and during physical exercise on a bicycle ergometer. These objective measures and the crewman's symptoms will be followed as they develop. If total changes, or rates of change, in these measurements are exceeded, the test will be terminated and only re-

PRINCIPAL
COORDINATING
SCIENTIST: DR. PAUL RAMBAUT - MANNED SPACECRAFT CENTER

OBJECTIVE: ASSESS THE ALTERATION IN MUSCULOSKELETAL STATUS DURING ORBITAL SPACEFLIGHT; EVALUATE WATER, ELECTROLYTE, AND HORMONAL CHANGES; DETERMINE NUTRITIVE REQUIREMENTS.

EXPERIMENTS		PRINCIPAL INVESTIGATOR
• MINERAL BALANCE	M071	WHEDON
• BONE MINERAL MEASUREMENT	M078	VOGEL & CAMERON
• BIOASSAY OF BODY FLUIDS	M073	LEACH/HUNTOON
• SPECIMEN MASS MEASUREMENT	M074	ORD
• BODY MASS MEASUREMENT	M172	ORD

FIGURE D-4: M070 -- Nutritional and Musculoskeletal Function

PRINCIPAL
COORDINATING
SCIENTIST: DR. ROBERT L. JOHNSON - MANNED SPACECRAFT CENTER

OBJECTIVE: ASSESS THE EFFECTS OF SPACEFLIGHT ON THE CIRCULATORY SYSTEM; DEFINE THE NAUTURE AND TIME COURSE OF ANY OBSERVED CHANGES; INVESTIGATE THE EFFICACY OF APPROPRIATE COUNTERMEASURES IN OBVIATING A PERFORMANCE DECREMENT WHICH MIGHT RESULT FROM THE ORTHOSTATIC HYPOTENSION SYNDROME.

EXPERIMENTS		PRINCIPAL INVESTIGATOR
• INFLIGHT LOWER BODY NEGATIVE PRESSURE	M092	R. JOHNSON
• VECTORCARDIOGRAM	M093	ALLENBACH

FIGURE D-5: M090 -- Cardiovascular Function

peated during the crewman's next cycle and, then, only after study of the results by the ground flight surgeon.

M110 - Hematology and Immunology Program

A series of tests have evolved during the flight programs to gain understanding as to the changes occurring within the blood (Figure D-6). Studies of cells and plasma volume changes, changes in the character of the cell, destruction rates of cells, etc. will be continued. Gradually, additional studies have been added to include hormonal excretion, endocrine production and excretion, and the ability of the body to maintain its immunity response. These will be further extended during the Skylab flights. The tests are all pre- and postflight tests since no blood will be drawn during flight, except in the case of an infection. The Inflight Medical Support System (IMSS) does have the capability to do blood counts, blood smear and staining. In these latter cases, a finger sample will be used.

M130 - Neurophysiology

There have been several occurrences of motion sickness in the United States and Soviet flights. In the U.S. flights, motion sickness symptoms did not occur when test pilots were the crewmen. On Apollo, however, when crewmen who were not test pilots began to fly in a spacecraft which permitted them to move about, some of these crewmen described an initial period of motion sickness from which they spontaneously recovered within the first three to four days. No symptoms then recurred. An experiment to assess the sensitivity of the vestibular apparatus will be performed (Figure D-7) to establish sensitivity to motion and position sensation.

There have been some confusing reports from the United States flights concerning the efficiency and quality of sleep. Crewmen have described and have demonstrated (using heart rate and restlessness) their obtaining only light sleep and subsequently becoming exhausted. Others reported no problem of sleeping at all. Fatigue after the flights has been a characteristic finding. An experiment is planned which will record the full eight hour sleep period on one astronaut using electroencephalography on several occasions during the mission. The tape recording of this sleep period will be analyzed by an onboard analyzer and the results showing duration, the stages of sleep, and duration in each stage will be transmitted. The tape from each of the full eight hour sleep periods will be returned with the crew, and postflight analysis will be used to verify the accuracy of the analysis report transmitted.

M170 - Pulmonary Function and Energy Metabolism

To complete the experimentation on understanding how man adjusts to the environment, and experimental group has been designed to determine the metabolic rates while performing measured tasks (Figure D-8). Oxygen consumption, carbon dioxide production and respiratory quotient will be determined while exercising on a bicycle ergometer. The vectorcardiogram will also be used while exercising to show changes in the heart response to calibrated workloads. Limits will be placed upon the exercise program in much the same manner as described for the lower body negative pressure device. Heart rate and blood pressure will also be measured.

PRINCIPAL
COORDINATING
SCIENTIST: DR. STEPHEN L. KIMSEY - MANNED SPACECRAFT CENTER

OBJECTIVE: DESCRIBE THE QUALITATIVE AND QUANTITATIVE CHANGES TO THE HEMATOLOGY AND IMMUNOLOGY SYSTEMS ATTRIBUTABLE TO THE CONDITIONS OF SPACEFLIGHT. SPECIFIC INVESTIGATION WILL EXPLORE THE AREAS OF FORMED BLOOD ELEMENT PHYSIOLOGY, HEMOSTASIS, HUMORAL IMMUNITY, CELLULAR IMMUNE STATUS, AND LEUKOCYTE CHROMOSOME ABERRATION FREQUENCIES.

EXPERIMENTS		PRINCIPAL INVESTIGATOR
• CYTOGENETIC STUDIES OF BLOOD	M111	LOCKHART
• MAN'S IMMUNITY - IN VITRO ASPECTS	M112	RITZMANN LEVIN
• BLOOD VOLUME AND RED CELL LIFE SPAN	M113	P. JOHNSON
• RED BLOOD CELL METABOLISM	M114	MENGEL
• SPECIAL HEMATOLOGIC EFFECTS	M115	KIMSEY
• ZERO-G SINGLE HUMAN CELL	S015	MONTGOMERY

FIGURE D-6: M110 -- Hematology and Immunology Program

PRINCIPAL COORDINATING SCIENTIST: DR. MILTON R. DELUCCHI - MANNED SPACECRAFT CENTER

OBJECTIVE: INVESTIGATE AND EVALUATE EFFECTS OF THE SPACE ENVIRONMENT UPON THE NERVOUS SYSTEM OF MAN. THIS BODY SYSTEM DEMANDS PARTICULAR ATTENTION IN THAT IT CONSTITUTES THE SENSORY, MOTOR, AND COORDINATING MECHANISM FOR HUMAN PERFORMANCE AND BEHAVIOR.

EXPERIMENTS		PRINCIPAL INVESTIGATOR
• HUMAN VESTIBULAR FUNCTION	M131	GRAYBIEL
• SLEEP MONITORING	M133	FROST

FIGURE D-7: M130 -- Neurophysiology

PRINCIPAL COORDINATING SCIENTIST: EDWARD L. MICHEL - MANNED SPACECRAFT CENTER

OBJECTIVE: ASSESS THE EFFECTS OF SPACE MISSION ENVIRONMENTS ON THE MECHANICS OF BREATHING AND RESPIRATORY GAS EXCHANGE; CHARACTERIZE THE ALTERATION AFFECTED BY THIS ENVIRONMENT ON BODY MASS AND COMPOSITION; QUANTITATE THE ENERGY COSTS OF SPACE MISSION ORIENTED PHYSICAL ACTIVITY IN TERMS OF RESPIRATORY GAS METABOLISM

EXPERIMENTS		PRINCIPAL INVESTIGATOR
• METABOLIC ACTIVITY	M171	MICHEL
• BODY MASS MEASUREMENT	M172	ORD

FIGURE D-8: M170 -- Pulmonary Function and Energy Metabolism

Human body mass, as discussed in the M070 series, will be used to establish the daily status of the crewman in maintaining his mass or to establish the trend toward deconditioning as indicated by marked changes in his daily mass determinations.

M150 - Behavioral Effects

A series of tasks that requires varying levels of astronaut involvement has been selected for formal, periodic recording during the Skylab mission (Figure D-9). Filming will be set up in a manner that permits the postflight application of a grid to the film, as was done during the lunar surface missions. Through this technique, the crewman's approach to tasks, his variation in approaching tasks, and estimates of his efficiency in performing a class of tasks can be determined. Tasks ranging from gross motions to fine detailed work are currently being screened for final selection.

Summary

Table D-12 indicates the frequency with which each experiment of the Skylab medical investigative program will be performed. The experiments which are concerned with the critical status of the crewman's capability to continue will be scheduled daily. For the cardiovascular studies, which will be performed at three day intervals, there will be additional data collected from this area through the medical monitoring system.

From the analysis of flight data obtained to date and from the predictions of important changes in other body systems or functions to be expected within the 56-day Skylab mission, the six major areas discussed above have been selected. The planning of the experiments to address these six areas recognizes that each function cannot be viewed in isolation from all others. There is interplay between systems and body organs that effects each of the others. Therefore, the studies will look at the individual measurement but will not be completed until the integrated result of all measurements is completed.

As has been shown, there is a series of experiments planned for each of the six areas. Thus, several different views of the changes in the system or function will be gained. Integration of the data from each system or function and, in turn, the related data from the six functions should permit the development of a profile describing how the total man adjusts to the space environment. A similar analysis of his performance should provide a profile describing what he can and cannot do, what his contribution may be, the relative value of that contribution, etc. From the performance profile, the future role of man in spaceflight should be come clearer.

Successful completion of these experiments will provide the first elements of the new knowledge required to explain the nature and extent of human acclimatization to the spaceflight environment, as it occurs over the course of these missions, and will provide a real basis in this area for the planning of future missions. In addition, successful completion offers the potential of providing an early plateau of knowledge of the mechanisms which govern the physiological integrity of man.

PRINCIPAL COORDINATING SCIENTIST: DR. EDWARD C. MOSELEY - MANNED SPACECRAFT CENTER

OBJECTIVE: ASSESS MAN'S FUNCTIONAL ABILITY IN COMPLETING NECESSARY OPERATIONAL AND USEFUL SCIENTIFIC WORK DURING LONG DURATION SPACEFLIGHT CONDITIONS; DEVELOP AND APPLY TECHNIQUES TO ASSESS SPACECRAFT AND EQUIPMENT DESIGN FOR HABITABILITY; PROVIDE FUNCTIONAL GROUND AND INFLIGHT BEHAVIORAL MEASUREMENTS OF SENSORY MOTOR PERFORMANCE, AND IMPLEMENT EXPERIMENTAL AND CLINICAL METHODS FOR EVALUATING COMPLEX INFLIGHT BEHAVIORAL CHANGES ASSOCIATED WITH EXTENDED MISSIONS.

EXPERIMENTS		PRINCIPAL INVESTIGATOR
• TIME AND MOTION STUDY	M151	KUBIS

FIGURE D-9: M150 -- Behavioral Effects

TABLE D-12: Medical Experiment Repetitions

	28 DAY MISSION		56 DAY MISSION	
	# OF CREWMEN	TOTAL	# OF CREWMEN	TOTAL
M071	3	DAILY	3	DAILY
M073	3	DAILY	3	DAILY
M074	3	DAILY	3	DAILY
M172	3	DAILY	3	DAILY
M092	3	8	3	17
M093	3	8	3	17
M131	3	A 6 B 3	3	A 9 B 5
M133	1	15	1	21
M151	2	15	2	19
M171	3	5	3	8

APPENDIX E

RECOMMENDED LIMITS FOR CONTAMINANTS IN SPACE CABINS

APPENDIX E

RECOMMENDED LIMITS FOR CONTAMINANTS IN SPACE CABINS

Introduction

Evaluation of the contaminant hazard in space operations is a difficult problem that has not been totally solved. The many toxic substances and odors which can be generated by the hardware or crewmembers have been examined in great detail. However, the variables and unknowns are numerous and have, to date, necessitated continued study for spacecraft trace contaminant removal systems.

Two tables of maximum allowable limits for trace contaminants are given in this Appendix. Table E-1 includes data developed in the late 1960's by the National Academy of Sciences - National Research Council (NAS-NRC). The data are based on mission lengths up to 1000 days. The data in Table E-2 are currently being implemented as design criteria for trace contaminant removal systems for future spaceflights. Table E-2 data are based on 14-day average length missions. The data presented were taken from the references listed at the end of this Appendix.

Discussion

It should be noted that with present knowledge, none of the industrial air limits can be used with certainty either directly or by extrapolation for cabin environments. Although extrapolating equations have been proposed, in which all variables likely to affect toxicity were included, subsequent experimental animal work has shown that such a procedure cannot be relied on in any given case. The rate of metabolism varies unpredictably from one pollutant to another under conditions of continuous exposure relative to intermittent exposure. This parameter appears to be overriding, at least as far as animal studies indicate, but it must be acknowledged that animal studies are incapable of revealing the magnitude of several of the factors included in the extrapolation equations.

Industrial air limits also appear to be inadequate for extrapolation to the space cabin environment in terms of other critical factors of the environment such as pressure, atmosphere, relative humidity, radiation, temperature, and other factors. Even the 90-day exposure limits set for submarines are not directly applicable because of these variables. Efforts to use these values when mixtures of toxic materials are involved, as is almost always the case in aerospace situations, are not only meaningless but dangerous.

In view of the necessity for provisional limits of manned spaceflights of 90 to 1000 days' duration, the NAS-NRC committee derived the following criteria for trace contaminant control in manned spacecraft:

1) Contaminants must not produce significant adverse changes in the physiological, biochemical, or mental stability of the crew.

2) The spacecraft environment must not contribute to a performance decrement of the crew that will endanger mission objectives.

3) The spacecraft environment must not interfere with physical or biological experiments nor with medical monitoring.

For the purposes of these provisional criteria, the Committee assumed a spacecraft atmosphere ranging from 760 to 258 mm Hg total pressure, containing nitrogen as a diluent gas, oxygen sufficient to maintain normal alveolar partial pressure, and carbon dioxide below 5 mm Hg. Temperature and relative humidity witnin the comfort zone for the total pressure selected were assumed.

This rigorous approach is also consistent with scientific requirements. The NASA Space Medicine Advisory Group and the Respiratory Physiology Group of the Space Science Board's 1966 Summer Study have reaffirmed the principle that engineering exigencies should not dictate the environment: the environment must be supplied to provide the best medium for the experimental effort and for the mission profile. Thus, since one of the goals of prolonged manned spaceflight is to ascertain man's adaptability and response to the weightless environment, it is necessary to design manned spacecraft in such a fashion that the earth atmosphere or a similar one be provided in order not to prejudice the study of the one facet of spaceflight that cannot be duplicated on earth -- weightlessness.

The NAS-NRC, therefore, developed conservative air quality standards for prolonged manned missions on the following premises:

1) Any contamination of the spacecraft atmosphere may be detrimental.

2) Zero contamination level of the spacecraft atmosphere is impossible.

3) Available data will not permit certain prediction of the maximum contaminant concentration possible without degradation of the mission.

4) Provisional limit values can be established for some contaminants to serve as guidelines in design, development, and testing of future space systems.

5) These provisional limit values can, perhaps, ultimately be transformed into limit values, if sufficient data about the effects of continuous exposure to a single compound and to multiple compounds can be obtained.

The uncertainties in establishing even provisional limits for prolonged manned missions are many and range from engineering to environmental to toxicological considerations. Since the materials to be used in future spacecraft construction and the type of regenerative environmental control system(s) to be employed have not been determined, there are major uncertainties regarding

the kind and amount of air contaminants that will be present. There is also a major uncertainty as to how reduced pressure may alter the toxicity of contaminants.

A subject of further consideration is the fact that most of the available data have been obtained on subjects in a "normal" physiological state. The effect of stress, prolonged confinement, weightlessness, and other factors that might tend to alter man's normal physiology, and thus change his response to any given compound, cannot be accurately predicted at this time. For all these reasons, the limits recommended by the NAS-NRC Committee are provisional and subject to revision.

Table E-1 lists in alphabetic order chemicals or chemical groups which have been identified as contaminants associated with U.S. spacecraft, nuclear submarine environments and agents from fire or other emergencies. Unless specified otherwise, the recommended limit is the Threshold Limit Value (TLV) which covers exposures for 8 hours a day, 5 days per week at standard temperatures and pressures. Some of the provisional limits for other exposure periods are those recommended by the NAS-NRC.

In brief, the provisional long-term limits recommended were chosen with the objective of avoiding adverse health effects (either immediate or delayed), degradation of performance, and interference with physiological studies on crew members. The provisional 60-minute emergency limits are designed to avoid significant degradation in crew performance in emergencies and to avoid permanent health injury. They contain essentially no safety factor, and transitory effects may result. Because of the inadequacies of the data mentioned above (particularly the fact that most current toxicologic data are based on noncontinuous exposure), because of uncertainty as to synergism among chemicals, and because of the possibility of minor excursions above the ceiling limit, a safety factor has been applied to each 90- to 1000-day limit value. The magnitude of the safety factor differs according to the toxicologic category of the contaminant. If the contaminant is an irritant at the threshold of response, an estimated factor of 5 is included in the limit. If the contaminant is capable of producing systemic, irreversible injury, a factor of 20 is included.

The duration of exposure to which a limit value applies is determined by the type of response induced by a given contaminant. If an irritant was local (e.g., the butanones), the committee felt that, as long as the concentration was kept below the irritant level, no cumulative effects would occur. In such cases, the 90-day limit applies equally to a 1000-day mission. When, however, the contaminant has the potential for cumulative action, albeit at an exposure level well above the provisional limit for 90 days, a reduction appropriate to the seriousness of the response is made for the 1000-day mission. In such instances, a five-fold reduction in the 90-day limit has been arbitrarily made (e.g., chloroform, dioxane). The other non-TLV limits are those previously recommended for nuclear submarine exposures by the NAS-NRC Committee on Toxicology and accepted as valid for space cabins.

TABLE E-1: National Academy of Sciences - National Research Council (NAS-NRC) Recommended Limits for Space Cabin Atmospheres

Toxic Hazard Rating

1. SLIGHT: readily reversible effects
2. MODERATE: not severe enough to cause death or permanent injury
3. HIGH: may cause death or permanent injury after very short exposure to small quantities

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments
Acetaldehyde		200	General narcotic action on the CNS. Irritating to the eyes. High concentrations cause headache and stupefaction.
Acetic Acid		10	Irritating to the eyes and mucous membranes. Penetrates the skin easily and can cause dermatitis and ulcers.
Acetone		2000 for 24 hrs. 300 for 90 days	Narcotic in high concentrations
Acetylene	Systemic 1-2	2500 for 24 hrs. 2500 for 90 days	When mixed with oxygen, in proportions of 40% or more, a narcotic. A simple asphyxiant.
Acrolein		0.1	Particularly affects the membranes of the eyes and respiratory tract.
Acrylic Acid	Acute Local: 3		Irritant by ingestion and inhalation
Adipic Acid			Details unknown; toxicity probably slight.
Alkyl Nitrate			No physiological information available.
Alkyl Siloxanes			No specific physiological information available. Generally siloxanes are eye irritants.
Allyl Alcohol		2	Irritation of skin, eyes and mucous membranes. Systemic poisoning is possible.
Alumino Silicates		N	No physiological information available.
Ammonia		400 for 1 hr. 50 for 24 hrs. 25 for 90 days	

*Unless otherwise specified as provisional limits under normoxic conditions by the NAS-NRC the limits are given as TLV (Earth equivalent), covering exposures for 8 hrs/day, 5 days per week at standard temperatures and pressures.

TABLE E-1 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments
Ammonia, Anhydrous		50	Irritating to eyes and mucous membranes of respiratory tract. Irritation of the skin may occur, especially if it is moist.
Amyl Alcohol	Local:1 Systemic: 2-3		Vapor may be irritating to the eyes and upper respiratory tract.
Benzene		100 for 24 hrs. 1 for 90 days	Exposure to high concentrations (3,000 ppm) may result in acute poisoning; narcotic action on the CNS. A definite cumulative action on bone marrow from 100 ppm exposures.
Bisphenol A		5	As phenol.
1-3 Butadiene		1000	Vapors are irritating to eyes and mucous membranes. Inhalation of high concentrations can cause unconsciousness and death. If spilled on skin or clothing, it may cause burns or frostbite.
Butane	Systemic: 1-2		Simple asphyxiant. Produces drowsiness.
2 Butanone		100 for 60 min. 20 for 90 days 20 for 1000 days	Irritation of mucous membranes
Butene-1	Systemic: 2		An anesthetic and asphyxiant.
CIS-Butene-2			Details unknown. May act as a simple asphyxiant.
Trans-Butene-2			Toxicity unknown.
(N. -) Butyl Alcohol		100 (TLV) 10 for 90 days 10 for 1000 days	Irritation of the eyes with corneal inflammation, slight headache, slight irritation of the nose and throat and dermatitis of the fingers. Keratitis has also been reported.
Butyraldehyde	Local:1-2 Systemic: 2		Local: Irritant; Ingestion, Inhalation. Systemic: Ingestion, Inhalation.
Butyric Acid	Local:1 Systemic: 1		Local: Irritant; Ingestion, Inhalation. Systemic: Ingestion, Inhalation.

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments
Caprylic Acid			Details unknown. Irritating vapors can cause coughing. Experimental data suggest low toxicity.
Carbon Dioxide		25,000 for 1 hr. 10,000 for 24 hrs. 5,000 for 90 days	Inhalation. (See Oxygen-CO_2-Energy, No. 10.)
Carbon Disulfide		20	Narcotic and anesthetic effect in acute poisoning, with death following from respiratory failure. Sensory symptoms precede motor involvement. Liver, kidney and heart may be damaged.
Carbon Monoxide		50 200 for 1 hr. 200 for 24 hrs. 5 for 90 days 15 for 1000 days	Effect is predominantly one of asphyxia, due to formation of irreversible carboxyhemoglobin in blood. 1,000 to 2,000 ppm for 1 hr. is dangerous, 4,000 ppm is fatal in less than 1 hr.
Carbon Tetrachloride		10	Narcotic action. High concentrations produce unconsciousness, followed by death. After effects may include damage to kidneys, liver and lungs. 1,000 to 1,500 ppm for 3 hrs. may cause symptoms.
Carbonyl Fluoride		25 for 60 min.	Pulmonary irritation (animals)
Chlorine		1 1 for 24 hrs. 0.1 for 90 days	Irritating to mucous membranes. If lung tissues are attacked, pulmonary edema may result.
Chlorobenzene		75	Slight irritant. May cause kidney and liver damage upon prolonged exposure.
Chloroform		5 for 90 days 1 for 1000 days	Fatty infiltration of liver at toxicological threshold.
Chloroprene		25	Asphyxiant. Vapor is a central system depressant. Lowers blood pressure. In animals causes severe degenerative changes in the vital organs, especially kidneys and liver.

TABLE E-1 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments
Chloropropane			No physiological information available, but should have toxic properties similar to ethyl chloride.
Cupric Oxide	Local: 1 Systemic: 1-2		As the sublimed oxide, copper may be responsible for one form of metal fume fever.
Cyanamide	Systemic: 1-2		Causes an increase in respiration and pulse rate, lowered blood pressure and dizziness. There may be a flushed appearance of the face. Does not contain free cyanide.
Cyclohexane		300	May act as a simple asphyxiant.
Cyclohexanol		50	Local: irritant; ingestion, inhalation. Systemic: ingestion, inhalation, skin absorption.
Dichloromethane		25 for 90 days 5 for 1000 days	Reduction of voluntary activity at threshold (in animals).
2, 2 Dimethylbutane			Toxicity: details unknown.
1, 1 Dimethylcyclohexane			No physiological information available.
Trans-1, 2 Dimethylcyclohexane			No physiological information available.
Dimethyl Hydrazine		0.5	Can be absorbed through intact skin. May result in convulsive siezures, pulmonary edema and hemorrhage.
Dimethyl Sulphide			Toxicity: details unknown. Probably highly toxic.
1-4 Dioxane		100 10 for 90 days 2 for 1000 days	Repeated exposure has resulted in human fatalities, the affected organs being the liver and kidneys. Death results from acute hemorrhagic nephritis. Brains and lungs show edema.
Epichlorohydrin		5	In acute poisoning, death is the result of respiratory paralysis. Chronic poisoning is the result of kidney damage.

TABLE E-1 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M^3	Comments
Ethyl Acetate		400 40 for 90 days 40 for 1000 days	Irritating to mucous surfaces. Prolonged or repeated exposures cause conjunctival irritation and corneal clouding. High concentrations are narcotic and can cause congestion of the liver and kidneys.
Ethyl Alcohol		500 for 24 hrs. 100 for 90 days	No cumulative effect. Irritating to eyes and mucous membranes of upper respiratory tract. Narcotic properties.
Trans-1, ME-3 Ethylcyclohexane			No physiological information available.
Ethylene	Acute Systemic: 2		High concentrations cause anesthesia. A simple asphyxiant.
Ethylene Dichloride		50	Irritating to eyes and upper respiratory passages. Vapor causes a clouding of the cornea which may progress to endothelial necrosis. Strong narcotic action. Edema of the lungs in animals.
Ethylene Glycol	Local: 0-1 Systemic:	0.2 100 for 60 min.	If ingested, it causes initial central nervous system stimulation, followed by depression. Later, it causes kidney damage which may terminate fatally.
Ethyl Sulfide			Details unknown, but probably moderately toxic.
Fluoro Ethylenes			No specific physiological information available. Generally fluorinated compounds are potentially toxic because they yield fluorine, hydrofluoric acid, etc. after ingestion, which are toxic.
Formaldehyde		5 0.1 for 90 days 0.1 for 1000 days	Toxic effects are mainly irritation. If swallowed it causes violent vomiting and diarrhea which can lead to collapse, increased airway resistance (animals) at threshold.
Fluorotrichloromethane R-11		30,000 for 1 hr. 20,000 for 24 hrs. 1,000 for 90 days	

TABLE E-1 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M^3	Comments
Dichlorodifluoromethane		30,000 for 1 hr. 20,000 for 24 hrs. 1,000 for 90 days	
$F_2ClC-C\ ClF_2$ R-114		30,000 for 1 hr. 20,000 for 24 hrs. 1,000 for 90 days	
Freons		1000	High concentrations cause narcosis and anesthesia.
Hexachlorophene	Local:1		Strong concentrations may be irritating.
Hexamethylcyclotrisiloxane			No physiological information available. Generally siloxanes cause eye irritation.
Hexamethylene Diamine	Acute Local:2		Local: irritant; ingestion, inhalation-all present.
N-Hexane		500	Local: irritant; ingestion, inhalation. Systemic: inhalation, ingestion.
Hexene-1	Acute Local:2 Acute Systemic: 2		Local: irritant; ingestion, inhalation. Systemic: inhalation
Hydrocyanic Acid		10	Can be absorbed via intact skin. A true protoplasmic poison, combining in the tissues with the enzymes associated with cellular oxidation and rendering the oxygen unavailable to the tissues.
Hydrogen	Acute Systemic:1	3,000 for 24 hrs. 3,000 for 90 days	Inhalation
Hydrogen Chloride		10 for 1 hr. 4 for 24 hrs. 1 for 90 days	Irritating to the mucous membranes
Hydrogen Fluoride		8 for 1 hr. 1 for 24 hrs. 0.1 for 90 days	Inhalation may cause ulcers of the upper respiratory tract. Produces severe skin burns, slow in healing.
Hydrogen Sulfide		50 for 1 hr.	An irritant and an asphyxiant. The effect on the nervous system is one of depression with small amounts, stimulation with larger ones. Asphyxia is due to paralysis of the respiratory system.

TABLE E-1 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments
Indole			No physiological information available. May be considered an emetic after long exposure.
Isobutyl Alcohol	Acute Local:3 Acute Systemic: 2	100	Local: irritant; ingestion, inhalation. Systemic: ingestion, inhalation.
Isobutylene			Toxicity: details unknown. May have asphyxiant or narcotizing action.
Isoprene	Acute Local:2 Acute Systemic: 2		Concentrations of 5% are fatal.
Isopropyl Alcohol		400	Can cause corneal burns and eye damage. Acts as a local irritant and in high concentrations as a narcotic.
Lithium Hydroxide	Local:1 Systemic: 1-2		Large doses of lithium compounds have caused dizziness and prostration, particularly on a low sodium intake.
Maleic Acid	Acute Local:2		Irritant, ingestion, inhalation.
Manganese Oxide	Systemic: 2-3	5 mg per cubic meter of air	The central nervous system is the chief site of damage, usually after 1 to 3 years of exposure to heavy concentrations of dust or fumes.
Mercaptans	Acute Local:3 Systemic: 2-3	0.5	Local: irritant; inhalation Systemic: inhalation.
Mercury		0.1 mg per cubic meter of air	Chronic low grade exposure affects CNS and kidneys; may sensitize to oxygen toxicity and radiation.
Methane	Systemic: 1	5,000 for 24hrs. 5,000 for 90days	Inhalation
Methyl Acrylate		10	Chronic exposure has produced injury to lungs, liver and kidneys in experimental animals.

TABLE E-1 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments
Methyl Alcohol		200 for 24 hrs. 10 for 90 days	Distinct narcotic properties. Slight irritant to the mucous membranes. Main toxic effect is on the nervous system, particularly the optic nerves. Once absorbed, it is only very slowly eliminated; coma may last 2-4 days. A cumulative poison.
2-Methylbutanone		20 for 90 days 20 for 1000 days	Irritation of mucous membranes in man at threshold.
Methyl Chloride		100	Repeated exposure to low concentrations causes damage to the CNS, and less frequently to the liver, kidneys, bone marrow and cardiovascular system. Exposure to high concentrations may result in delirium, coma and death.
Methyl Chloroform		1,000 for 1 hr. 500 for 24 hrs. 200 for 90 days	Local: irritant by ingestion, inhalation Systemic: toxic by ingestion, inhalation
Methylene Chloride		500	Very dangerous to the eyes. Strong narcotic powers.
Methylethyl Ketone		200	Local irritation and narcosis.
Methyl Isopropyl Ketone		200	No physiological information available. In general it should have same irritant properties as low molecular weight ketones; i.e., eye, skin and respiratory tract irritant.
Methyl Methacrylate	Acute Local: 1 Systemic: 1		Local: irritant by ingestion, inhalation. Systemic: toxic by ingestion, inhalation.
Methyl Nitrate	Systemic: 2		Ingestion, inhalation
3-Methyl-Pentane			Details unknown; may have narcotic or anesthetic properties.
Methyl Salicylate	Local: 1-2 Acute Systemic: 3		Acute accident poisoning is not uncommon. Kidney irritation, vomiting and convulsions occur.

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments
Monoethanolamine		50 for 1 hr. 3 for 24 hrs. 0.5 for 90 days	A skin irritant and necrotizer; a central nervous system stimulant in low doses; a depressant at high doses.
Monomethylhydrazine		0.2	A respiratory irritant and convulsant at low doses.
Nitric Oxide		5	60-150-ppm-immediate irritation of throat and nose. Shortness of breath, restless, loss of consciousness and death may follow. 100-150 ppm for 30-60 minutes is dangerous.
Nitrogen Dioxide		10 for 1 hr. 1 for 24 hrs. 0.5 for 90 days	Highly toxic.
Nitrous Oxide	Acute Systemic: 2		Inhalation
Olefins			Prolonged exposure to high concentrations has led to liver damage and hyperplasia of the marrow in animals; no corresponding effects have been found in humans. Relatively innocuous.
Ozone		1.0 for 1 hr. 0.1 for 24 hrs. 0.02 for 90 days	Strong irritant action on the upper respiratory system.
N-Pentane	Acute Systemic: 1		Inhalation. Narcotic in high concentrations.
Phenol		5	Can be absorbed through intact skin. Main effect is on the CNS in acute poisoning. Death may result within 30 minutes to several hours of spilling on the skin.
Phosgene		1.0 for 1 hr. 0.1 for 24 hrs. 0.05 for 90 days	Irritating to eyes and throat. The main fatal effect is pulmonary edema.
Potassium Dichromate		0.1	A corrosive action on the skin and mucous membranes. Characteristic lesion is a deep ulcer, slow in healing. Chromate salts have been associated with cancer of the lungs.

TABLE E-1 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments
Propane	Acute Systemic: 1	1000	Inhalation
N-Propylacetate		200	Causes narcosis and is somewhat irritating. Definite evidence of habituation - not likely to cause chronic poisoning.
Propylene	Acute Systemic: 2		Inhalation. A simple asphyxiant.
Silicic Acid			Toxicity slight, but dangerous in weightless conditions as it may form powders if not well confined.
Skatole			No specific physiological information available. May be considered an emetic after lengthy exposures.
Sulfur Dioxide		10 for 1 hr. 5.0 for 24 hrs. 1.0 for 90 days	Irritating to nose and throat. MAC for 30-60 minutes exposure is 50-100 ppm. 400-500 ppm immediately dangerous to life.
Terepthalic Acid			No specific physiological information available. A mild irritant with low acute oral toxicity.
Tetrachloroethylene		100	Toxic by inhalation, prolonged or repeated contact with the skin, or mucous membranes or when ingested. Liquid can cause injuries to the eyes, irritation of the nose and throat.
Tetrafluoroethylene Inhibited			Toxicity: can act as an asphyxiant and may have other toxic properties.
Toluene		100 for 24 hrs.	Impairment of coordination and reaction time. Few cases of acute toluene poisoning.
Toluene 2,4 di-isocyanate		0.02	Severe dermatitis and bronchial spasm. Particularly irritating to the eyes.
Tri-aryl phosphates		5.0	As cresol. Ingestion, inhalation skin absorption.

TABLE E-1 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments
1, 1, 1-Trichloroethane		1,000 for 1 hr. 500 for 24 hrs. 200 for 90 days	Narcotic at low levels. High levels may affect liver and lungs.
Trichloroethylene		100 10 for 90 days 2 for 1000 days	Inhalation of high concentrations causes narcosis and anesthesia. A form of addiction has been observed. Death from cardiac failure due to ventricular fibrillation has been reported.
1, 1, 2-Trichloro, 1, 2, 2-Trifluoroethane (Freon 113) and congeners		30,000 for 60 min. 1,000 for 90 days 200 for 1000 days	CNS and cardiovascular effects at threshold in animals.
1, 1, 3-Trimethylcyclohexane			No physiological information available. Suspect it should be a skin irritant (solvent action) and irritant of the respiratory tract.
Urea			Toxicity: no importance as an industrial hazard. Slightly dangerous when heated.
Valeric Acid			Toxicity: details unknown. Nauseating. See Butyric Acid.
Vinyl Acetate	Local: 1 Acute Systemic: 1		Local: Irritant Systemic: Inhalation.
Vinyl Chloride		500	In high concentrations it acts as an anesthetic. Causes skin burns by rapid evaporation and consequent freezing.
Vinylidene Chloride		5 for 30 to 90 days	Details unknown. See Vinyl Chloride.
Xylene		100 for 24 hrs.	Local: irritant. Systemic: inhalation, skin absorption.

TABLE E-2: Maximum Concentration and Production Rate of Trace Contaminants for Spacecraft (14 Days Duration)

Contaminant	Production Rates			Maximum Allowable Concentration (mg/m^3)
	Non-Biological (gm/day)	Biological (gm/day)	Total (gm/day)	
Acetone	10.20	0.0059	10.20	240
Acetaldehyde	2.50	0.0023	2.50	36
Acetic Acid	0.25		0.25	2.5
Acetylene	2.50		2.50	180
Acetonitrile	0.25		0.25	7
Acrolein	0.25		0.25	0.25
Allyl Alcohol	0.25		0.25	0.5
Ammonia	2.50	12.	14.50	3.5
Amyl Acetete	0.25		0.25	53
Amyl Alcohol	0.25		0.25	36
Benzene	2.50		2.50	8
n-Butane	2.50		2.50	180
iso-Butane	0.25		0.25	180
Butene-1	2.50		2.50	180
cis-Butene-2	0.25		0.25	180
trans-Butene-2	2.50		2.50	180
1, 3 Butadiene	2.50		2.50	220
iso-Butylene	0.25		0.25	180
n-Butyl Alcohol	2.50	.036	2.54	30
iso Butyl Alcohol	0.25		0.25	30
sec-Butyl Alcohol	0.25		0.25	30

TABLE E-2 (continued)

Contaminant	Production Rates			Maximum Allowable Concentration (mg/m^3)
	Non-Biological (gm/day)	Biological (gm/day)	Total (gm/day)	
Butyl Acetate	0.25		0.25	71
Butraldehydes	0.25		0.25	70
Butyric Acid	0.25		0.25	14
Carbon Disulfide	0.25		0.25	6
Carbon Monoxide	2.50	.4	2.9	29
Carbon Tetrachloride	0.25		0.25	6.5
Carbonyl Sulfide	0.25		0.25	25
Chlorine	0.25		0.25	1.5
Chloroacetone	0.25		0.25	100
Chlorobenzene	0.25		0.25	35
Chlorofluoromethane	0.25		0.25	24
Chloroform	2.50		2.50	24
Chloropropane	0.25		0.25	84
Caprylic Acid			0.25	155
Cumene	0.25		0.25	25
Cyclohexane	2.50		2.50	100
Cyclohexene	0.25		0.25	100
Cyclohexanol	0.25		0.25	20
Cyclopentane	0.25		0.25	100
Cyclopropane	0.25		0.25	100
Cyanamide	0.25		0.25	45
Decalin	0.25		0.25	5.0

TABLE E-2 (continued)

Contaminant	Production Rates			Maximum Allowable Concentration (mg/m^3)
	Non-Biological (gm/day)	Biological (gm/day)	Total (gm/day)	
1, 1 Dimethyl cyclohexane	0.25		0.25	120
trans 1, 2, Dimethyl Cyclohexane	0.25		0.25	120
2, 2 Dimethyl butane	0.25		0.25	93
Dimethyl Sulfide	0.25		0.25	15
1, 1 Dichloroethane	2.50		2.50	40
Di iso Butyl Ketone	0.25		0.25	29
1, 4 Dioxane	2.50		2.50	36
Dimethyl Furan	0.25		0.25	3.0
Dimethyl Hydrazine	0.25		0.25	0.1
Ethane	2.50		2.50	180
Ethyl Alcohol	2.50	.12	2.62	190
Ethyl Acetate	2.50		2.50	140
Ethyl Acetylene	0.25		0.25	180
Ethyl Benzene	0.25		0.25	44
Ethylene Dichloride	0.25		0.25	40
Ethyl Ether	2.50		2.50	120
Ethyl Butyl Ether	0.25		0.25	200
Ethyl Formate	2.50		2.50	30
Ethylene	2.50		2.50	180
Ethylene Glycol	0.25		0.25	114
trans 1, Methyl 3 Ethyl Cyclohexane	0.25		0.25	117

TABLE E-2 (continued)

Contaminant	Production Rates			Maximum Allowable Concentration (mg/m^3)
	Non-Biological (gm/day)	Biological (gm/day)	Total (gm/day)	
Ethyl Sulfide	0.25		0.25	97
Ethyl Mercaptan	0.25		0.25	2.5
Freon 11	2.50		2.50	560
Freon 12	2.50		2.50	500
Freon 21	0.25		0.25	420
Freon 22	0.25		0.25	350
Freon 23	0.25		0.25	12
Freon 113	0.25		0.25	700
Freon 114	2.50		2.50	700
Freon 114 unsym	0.25		0.25	700
Freon 125	0.25		0.25	25
Formaldehyde	0.25		0.25	0.6
Furan	0.25		0.25	3
Furfural	0.25		0.25	2
Hydrogen	2.50	.6	3.10	215
Hydrogen Chloride	0.25		0.25	0.15
Hydrogen Fluoride	0.25		0.25	0.08
Hydrogen Sulfide		0.0007	.0009	1.5
Heptane	0.25		0.25	200
Hexene-1	0.25		0.25	180
n-Hexane	2.50		2.50	180
Hexamethylcyclotri-sihexane	0.25		0.25	240

TABLE E-2 (continued)

Contaminant	Production Rates			Maximum Allowable Concentration (mg/m^3)
	Non-Biological (gm/day)	Biological (gm/day)	Total (gm/day)	
Indole	0.25	1.2	1.45	126
Isoprene	0.25		0.25	140
Methylene Chloride	2.50		2.50	21
Methyl Acetate	2.50		2.50	61
Methyl Butyrate	0.25		0.25	30
Methyl Chloride	0.25		0.25	21
2-Methyl-1 Butene	0.25		0.25	1430
Methyl Chloroform	2.50		2.50	190
Methyl Furane	0.25		0.25	3
Methyl Ethyl Ketone	2.50		2.50	59
Methyl Isobutyl Ketone	0.25		0.25	41
Methyl Iscpropyl Ketone	2.50		2.50	70
Methyl Cyclohexane	0.25		0.25	200
Methyl Acetylene	0.25		0.25	165
Methyl Alcohol	2.50	.12	2.62	26
3-Methyl Pentane	0.25		0.25	295
Methyl Methacrylate	0.25		0.25	41
Methane	29.5	7.2	36.7	1720
Mesitylene	0.25		0.25	2.5
mono Methyl Hydrazine	0.25		0.25	0.C35

TABLE E-2 (continued)

Contaminant	Production Rates			Maximum Allowable Concentration (mg/m^3)
	Non-Biological (gm/day)	Biological (gm/day)	Total (gm/day)	
Methyl Mercaptan			0.25	2
Naphthalene	0.25		0.25	5.0
Nitric Oxide	0.25		0.25	32
Nitrogen Tetroxide	0.25		0.25	1.8
Nitrogen Dioxide	0.25		0.25	0.9
Nitrous Oxide	0.25		0.25	47
Octane	0.25		0.25	235
Propylene	2.50		2.50	180
iso-Pentane	2.50		2.50	295
n-Pentane	2.50		2.50	295
Pentene-1	0.25		0.25	180
Pentent-2	0.25		0.25	180
Propane	2.50		2.50	180
n-Propyl Acetate	0.25		0.25	84
n-Propyl Alcohol	2.50		2.50	75
iso-Propyl Alcohol	2.50		2.50	98
n-Propyl Benzene	0.25		0.25	44
iso-Propyl Chloride	0.25		0.25	260
iso-Propyl Ether	0.25		0.25	120
Proprionaldehyde	0.25		0.25	30
Propionic Acid	0.25		0.25	15
Propyl Mercaptan			0.25	82

TABLE E-2 (continued)

Contaminant	Production Rates			Maximum Allowable Concentration (mg/m^3)
	Non-Biological (gm/day)	Biological (gm/day)	Total (gm/day)	
Propylene Aldehyde	0.25		0.25	10
Pyruvic Acid		4.53	4.53	0.9
Phenol	0.25	4.53	4.78	1.9
Skatol			0.25	141
Sulfur Dioxide	0.25		0.25	0.8
Styrene	0.25		0.25	42
Tetrachloroethylene	0.25		0.25	67
Tetrafluoroethylene	0.25		0.25	205
Tetrahydrofurane	0.25		0.25	59
Toluene	2.50		2.50	75
Trichloroethylene	2.50		2.50	52
1, 2, 4 Trimethyl Bezene	0.25		0.25	49
1, 1, 3 Thrimethyl cyclohexane	0.25		0.25	140
Valeraldehyde			0.25	70
Valeric Acid			0.25	110
Vinyl Chloride	2.50		2.50	130
Vinyl Methyl Ether	0.25		0.25	60
Vinyldene Chloride	0.25		0.25	20
O-Xylene	2.50		2.50	44
m-Xylene	2.50		2.50	44
p-Xylene	2.50		2.50	44

CHEMICAL SYNONYMS FOR TABLES E-1 AND E-2

2-Buranone = Methyl ethyl ketone

Chlorodifluoromethane = Freon 22

Crotonaldehyde = propylene aldehyde

Decahydronaphthalene = Decalin

1, 2 Dichloroethane = Ethylene chloride = Ethylene dichloride

Dichlorodifluoromethane = Freon 12

Dichlorofluoromethane = Freon 21

Dichlorotetrafluorethane = Freon 114

p-Dioxane = 1, 4 Dioxane

2-Methyl butanone-3 = 3-Methyl 2 Butanone = Methyl isopropyl ketone

Methoxy ethane = Vinyl methyl ether

Propene = Propylene

Propyne = Propine + Methyl acetylene

Pentafluoroethane = Freon 125

Perchloroethylene = Tetrachloroethylene

Trichlorofluoromethane = Freon 11

Trichlorotrifluoroethane = Freon 113

Trifluoromethane = Fluoroform = Freon 23

1, 3, 5 Trimethyl benzene = mesitylene

REFERENCES

Cox, R. P. Potential C.N.S. Effects of Selected Closed System Contaminants on Continuous Exposure, DAC-SM-47840, Douglas Aircraft Co., Inc., Santa Monica, Calif., June 1965.

Lovelace Foundation for Medical Education and Research: Compendium of Human Responses to the Aerospace Environment, Vol. III, Section 13, November 1968.

Manned Spacecraft Center: Design Requirements for Contaminant Removal, Space Station Regenerative Life Support System Prototype, Houston, Tex., 1971.

National Academy of Sciences - National Research Council: Emergency Exposure Limits for Atmospheric Contaminants in Nuclear Submarines, Committee on Toxicology, A Letter from the Comm. to Chief, Bureau of Medicine and Surgery, Washington, D.C., May 24, 1966.

National Academy of Sciences - National Research Council: Space Science Board, Report of the Ad Hoc Committee on Air Quality Standards in Space Flight, Atmospheric Contaminants in Spacecraft, Washington, D.C., 1967.

Sax, N. I. Dangerous Properties of Industrial Materials, 2nd Edition, Reinhold, N.Y., 1963.

APPENDIX F

METEOROID ENVIRONMENT MODEL

APPENDIX F

METEOROID ENVIRONMENT MODEL

CRITERIA

The meteoroid and lunar ejecta flux-mass models and the associated particle density and velocity values presented in the following subsections should be used to establish the meteoroid environment for engineering application to space missions in near-earth orbit.

METEOROID ENVIORNMENT

The meteoroid environment model encompasses only particles of cometary origin and is composed of sporadic meteoroids in the mass range between 10^{-12} and 1 gram and stream meteoroids in the mass range from 10^{-6} to 1 gram.

Average Total Meteoroid Environment

The average total meteoroid (average sporadic plus a derived average stream) environment is to be used for preliminary design and for mission periods that cannot be specified. When the mission launch date and duration are specified later in the design, the probability of stream damage should be evaluated.

Particle Density:

The mass density is 0.5 gm/cm^3 for all meteoroid sizes.

Particle Velocity:

The average meteoroid velocity is 20 km/sec with a probability-velocity distribution as given in Figure F-1.

Flux-Mass Model:

The average cumulative meteoroid flux-mass model is shown in logarithmic form in Figure F-2 and is described mathematically as follows:

$10^{-6} \le m \le 10^{0}$ $\quad \mathrm{Log}_{10}\ N_t = -14.37 - 1.213 \log_{10} m$

$10^{-12} \le m \le 10^{-6}$ $\quad \mathrm{Log}_{10}\ N_t = -14.339 - 1.584 \log_{10} m - 0.063 (\log_{10} m)^2$

where

N_t = number of particles of mass m or greater per square meter per second*
m = particle mass in grams

*Log_{10} N (particles/ft^2/day) = Log_{10} N (particles/m^2/sec) + 3.906

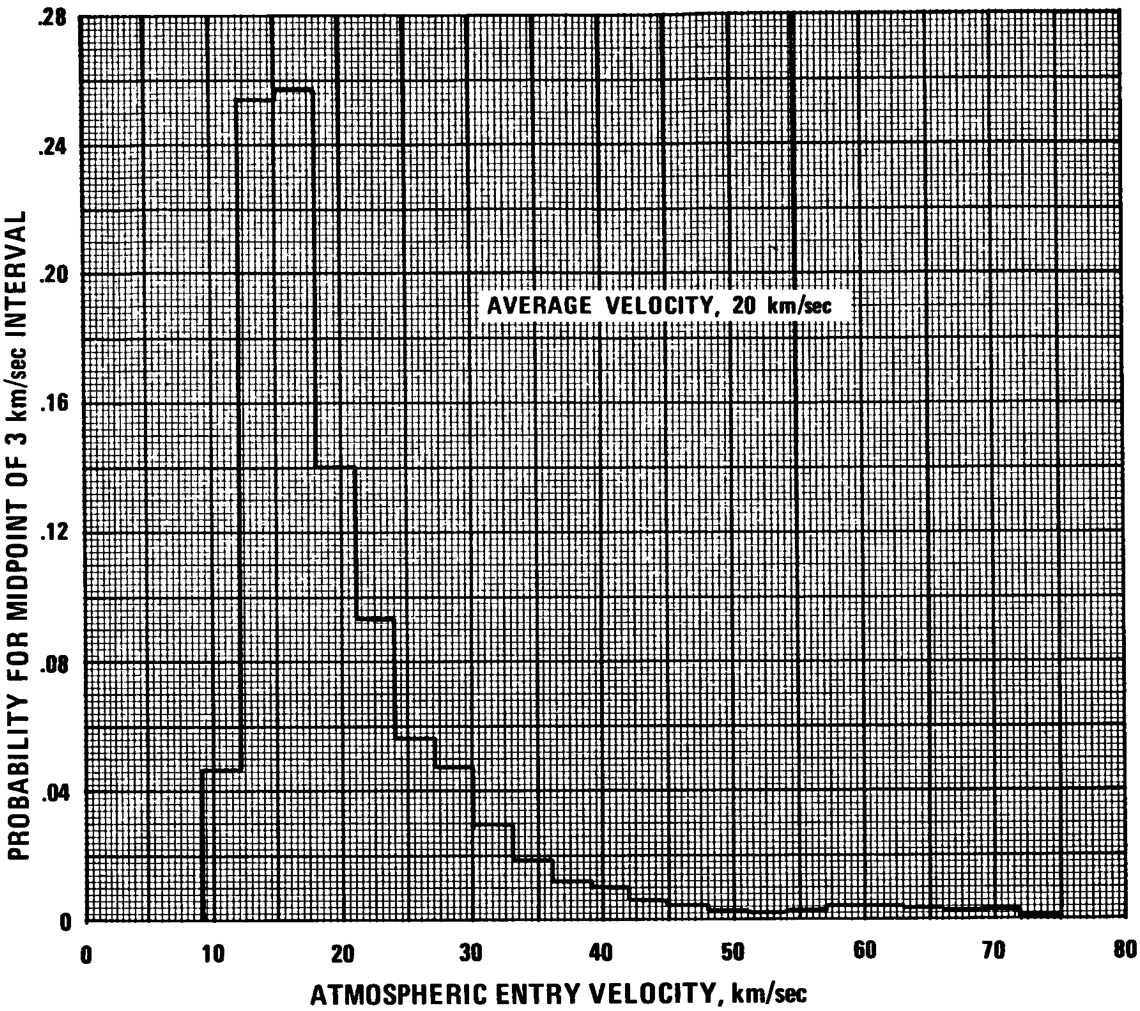


FIGURE F-1: Probability-Velocity Distribution for Sporadic Meteoroids

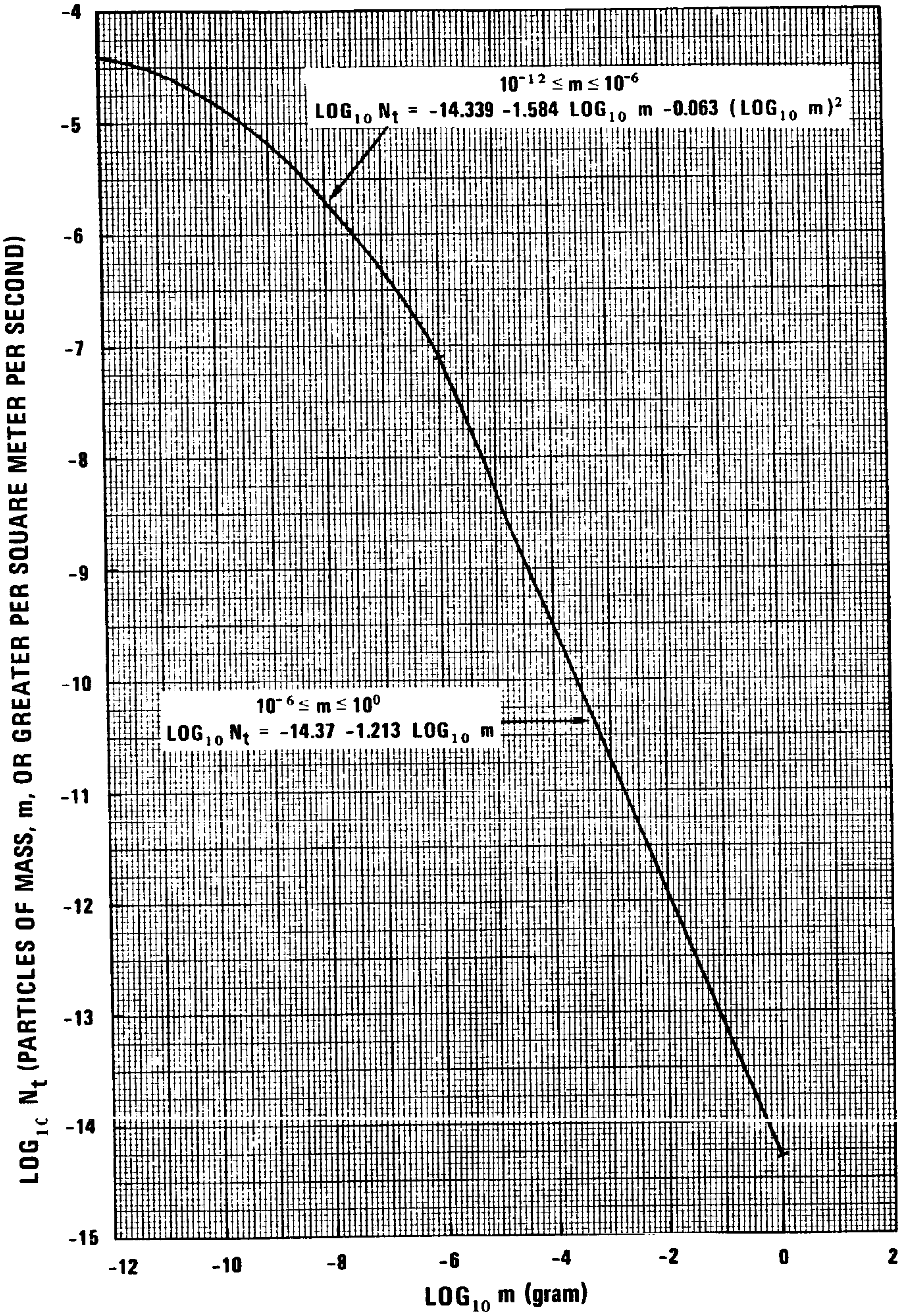


FIGURE F-2: Average Cumulative Total Meteoroid Flux-Mass Model for 1 A.U.

The gravitationally focused, unshielded flux, N_t, must be multiplied by an appropriate defocusing factor for earth, G_e, and, if applicable, by the shielding factor. The G_e factor applies to all missions and is to be obtained from Figure F-3. The body shielding factor for randomly oriented spacecraft, ζ, is calculated by the method given in Figure F-4 and applies to all missions. For oriented spacecraft, the effects of body shielding on the number of impacts as seen by parts of the spacecraft must be determined on a unique basis.

Sporadic Meteoroids

The average sporadic meteoroid environment is to be used in conjunction with the specific stream meteoroid environment in design of a vehicle with a specified mission period (launch date and duration).

Particle Density:

The mass density is 0.5 gm/cm^3 for all sporadic particle sizes.

Particle Velocity:

The average sporadic particle velocity is 20 km/sec with a probability -velocity distribution, as given in Figure F-1.

Flux-Mass Model:

The average cumulative sporadic flux-mass model is shown in logarithmic form in Figure F-5 and is described mathematically as follows:

$10^{-6} \leq m \leq 10^{0}$ $\qquad$ $\mathrm{Log}_{10} N_{sp} = -14.41 \; -1.22 \; \log_{10} m$

$10^{-12} \leq m \leq 10^{-6}$ $\qquad$ $\mathrm{Log}_{10} N_{sp} = -14.339 - 1.584 \log_{10} m - 0.063 (\log_{10} m)^2$

where

N_{sp} = number of sporadic particles of mass m or greater per square meter per second
m = particle mass in grams

The gravitationally focused unshielded flux, N_{sp}, must be multiplied by an appropriate defocusing factor for the earth, G_e, and, if applicable, by the shielding factor. The G_e factor applies to all missions and is to be obtained from Figure F-3. The body shielding factor for randomly oriented spacecraft, ζ, is calculated by the method given in Figure F-4 and applies to all missions. For oriented spacecraft, the effects of body shielding on the number of impacts as seen by parts of a spacecraft must be determined on a unique basis.

Stream Meteoroids

The specific stream environment is to be used in the design of a vehicle with a specified mission period (launch date and duration) and as a means of

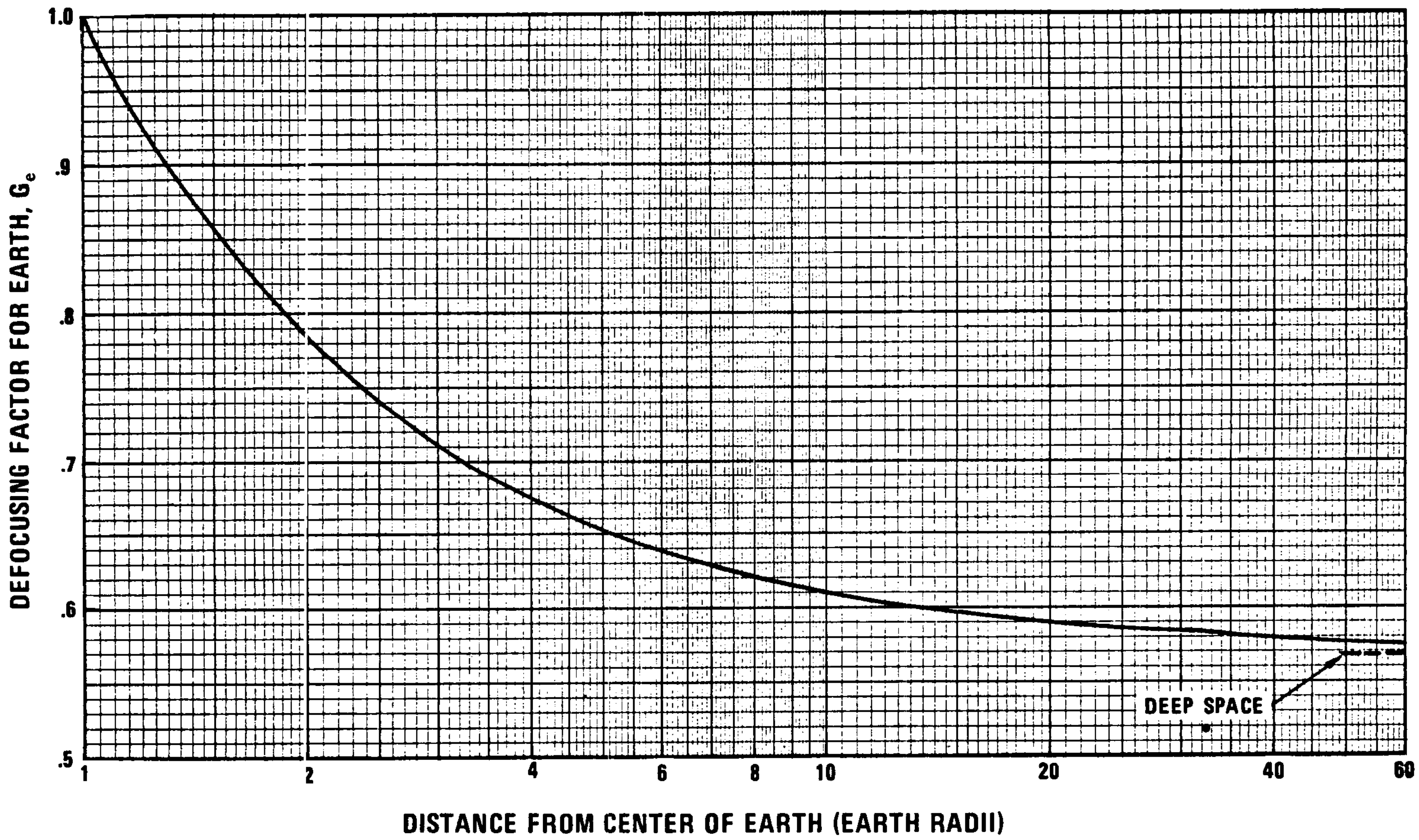
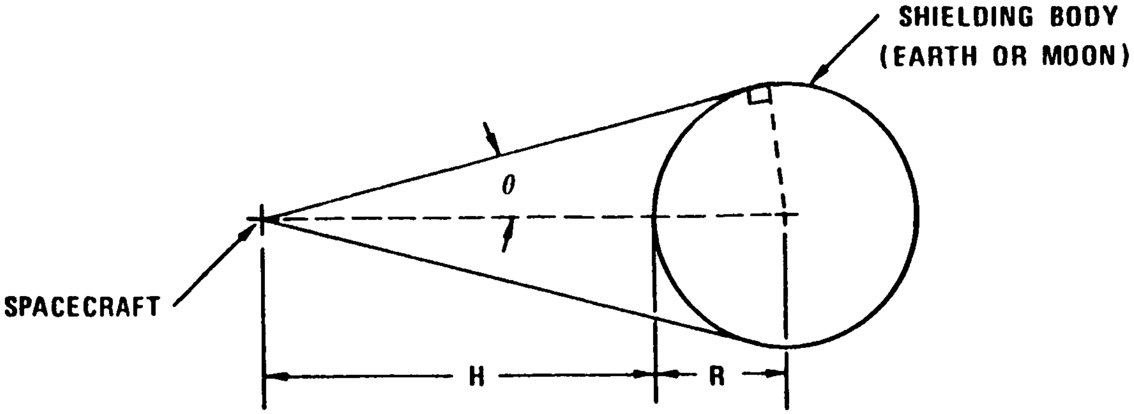


FIGURE F-3: Defocusing Factor Due to Earth's Gravity for Average Meteoroid Velocity of 20 km/sec



BODY SHIELDING FACTOR, ζ : (Defined as ratio of the shielded to unshielded flux)

$$\zeta = \frac{1 + \cos\theta}{2}$$

WHERE:

$$\sin\theta = \frac{R}{R + H}$$

R Radius of Shielding Body
H Altitude above Surface

Subscripts:
e Earth
m Moon

FIGURE F-4: Method for Determining Body Shielding Factor for Randomly Oriented Spacecraft

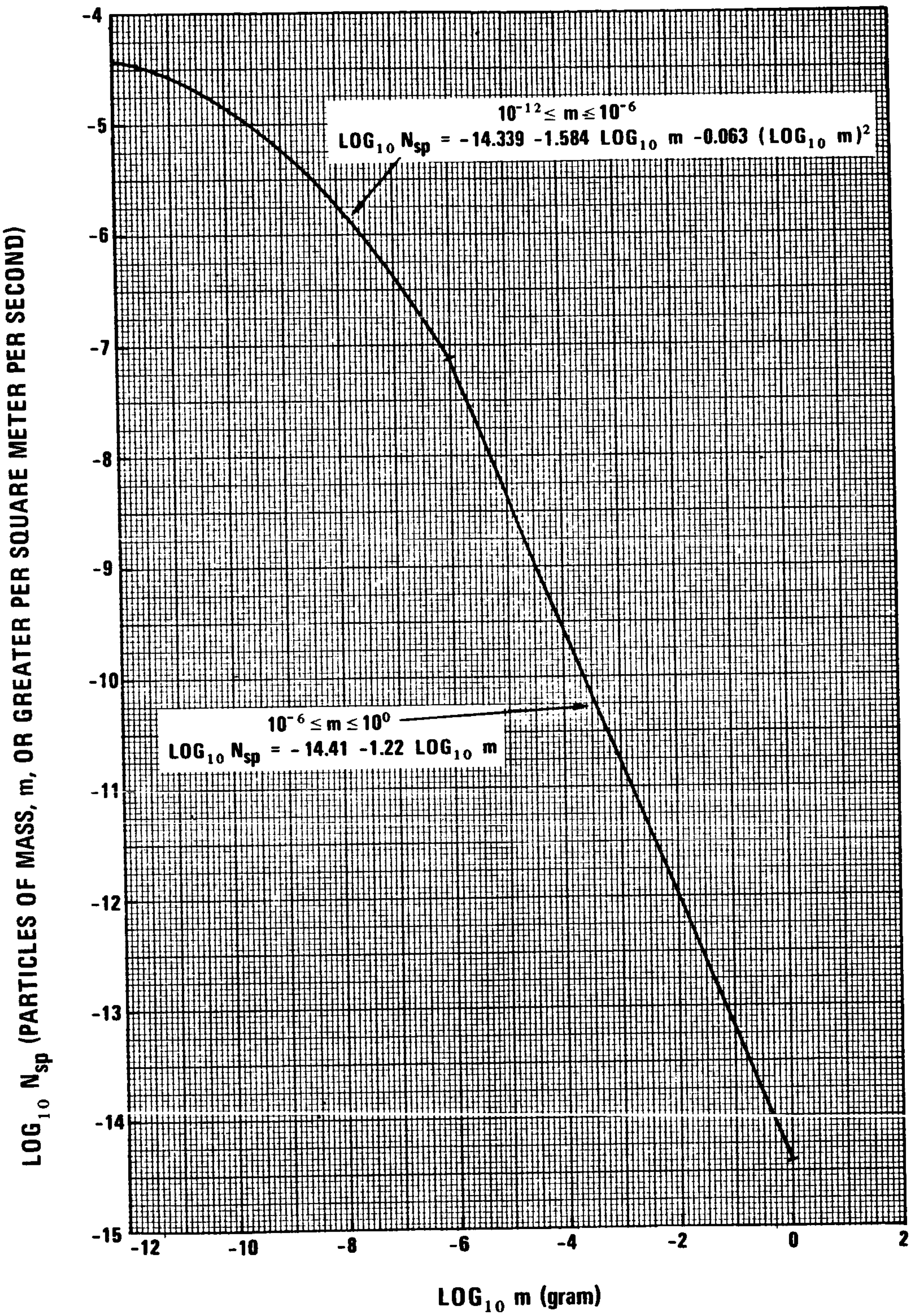


FIGURE F-5: Average Cumulative Sporadic Meteoroid Flux-Mass Model for 1 A.U.

determining the probability of stream damage to a spacecraft that has been designed to an average annual total meteoroid environment.

Particle Density:

The mass density is 0.5 gm/cm^3 for all stream particle sizes.

Particle Velocity:

The particle velocity of each stream is that given in Table F-1.

Flux-Mass Model:

The cumulative flux-mass model applicable to each individual stream is described mathematically as follows:

$$10^{-6} \leq m \leq 10^{0} \qquad \text{Log}_{10}\ N_{st} = -14.41 - \log_{10} m - 4.0 \log_{10}\left(\frac{V_{st}}{20}\right) + \log_{10} F$$

where

N_{st} = number of stream particles of mass m or greater per square meter per second
m = particle mass in grams
V_{st} = geocentric velocity of each stream in km/sec from Table F-1.
F = integrated average ratio of cumulative flux of stream to the average cumulative sporadic flux as calculated from Figure F-6 for the portion of the stream's duration within the mission period

No gravitational factor is to be applied to the flux of a specific stream. Similarly, there is no shielding effect unless a shielding body eclipses the spacecraft relative to the radiant of a stream as given in Table F-2. When an eclipse occurs, the flux of that specific stream is zero.

LUNAR EJECTA ENVIRONMENT

The lunar ejecta environment encompasses the lunar particles ejected from impacts of meteoroids on the lunar surface. In addition to the hazard of meteoroids in extravehicular activities and other operations on or near the lunar surface, lunar ejecta must be considered. The lunar ejecta environment given herein is to be used from the lunar surface to an altitude of 30 km. The effects of the ejecta environment must be considered separately from meteoroids because of their different velocity regimes.

Particle Density:

The mass density is 2.5 gm/cm^3 for all ejecta particle sizes.

Particle Velocity:

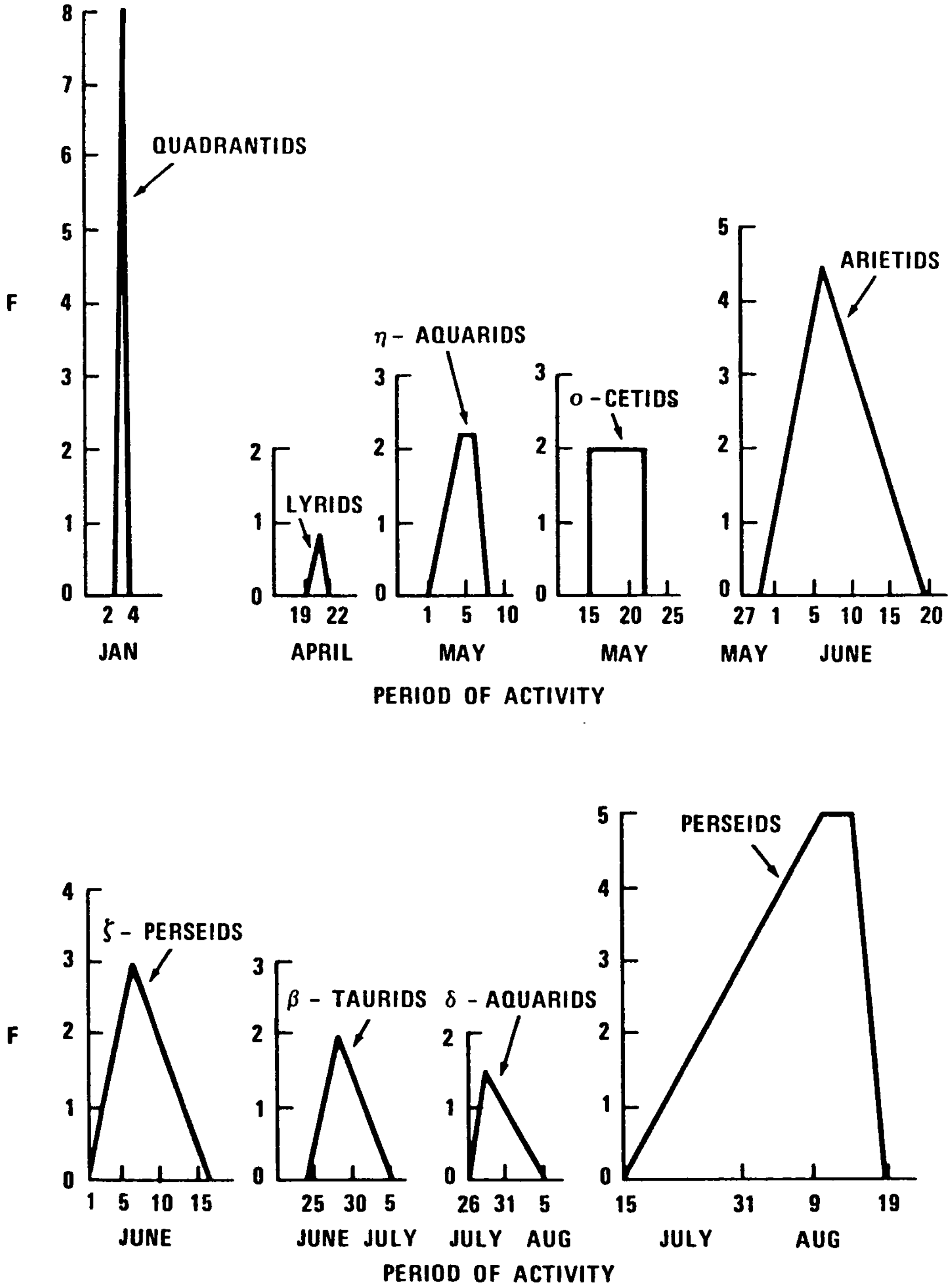
The average ejecta velocity is 0.1 km/sec for all ejecta particle sizes.

TABLE F-1

MAJOR METEOROID STREAMS

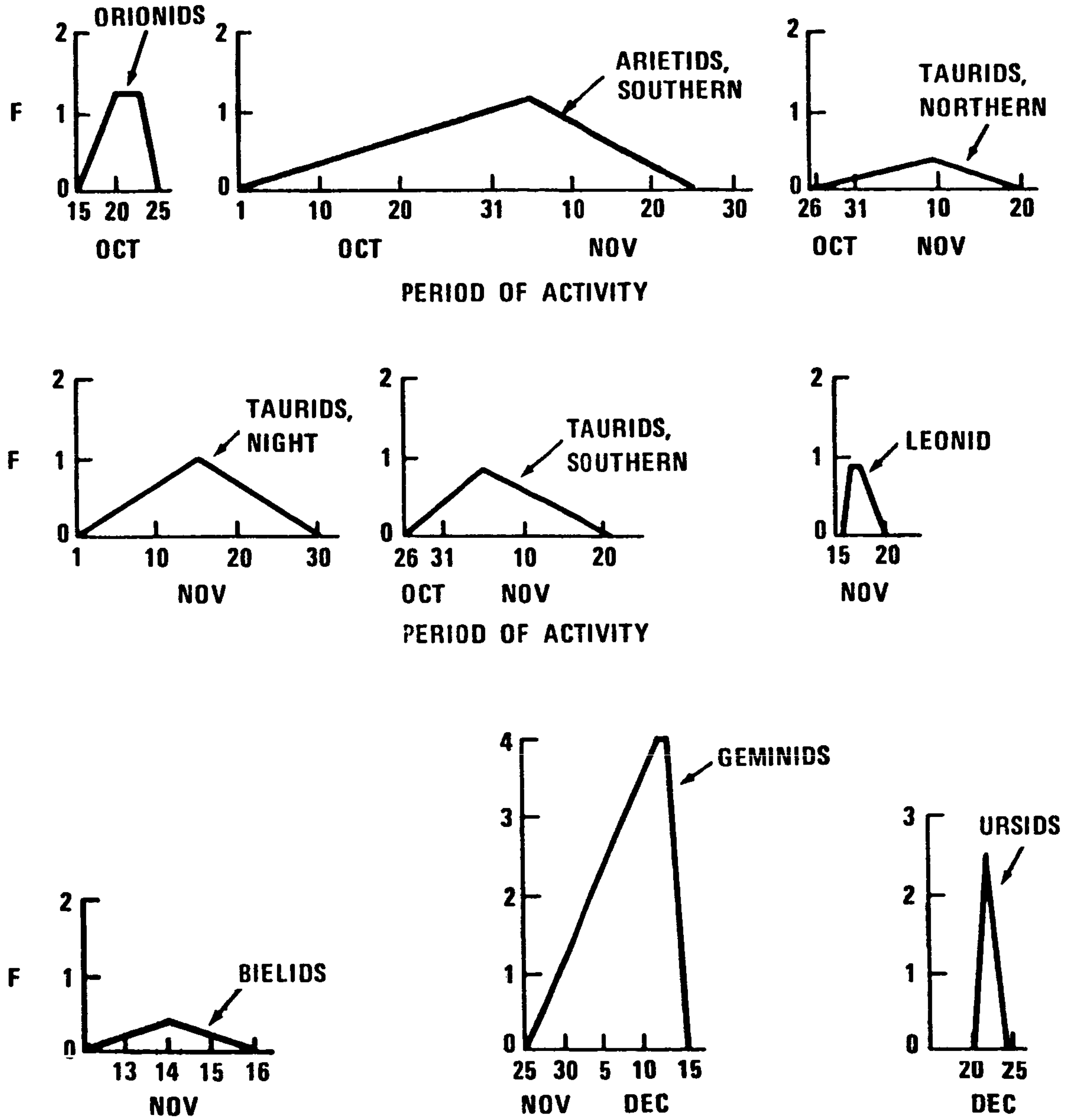
Name	Period of activity	Date of maximum	F_{max} (a)	Orbital elements (defined in fig.5)							Velocity
				Ω, deg.	π, deg.	ω, deg.	ι, deg.	ϵ	q, A. U.	a, A. U.	Geocentric, km/sec
Quadrantids	Jan. 2 to 4	Jan. 3	8.0	282	92	166	67	0.46	0.97	1.7	42
Lyrids	Apr. 19 to 22	Apr. 21	0.85	30.5	--	210	81	0.88	0.90	--	48
η - Aquarids	May 1 to 8	May 4 to 6	2.2	45	152	108	162	0.96	0.86	17.95	64
o - Cetids	May 14 to 23	May 14 to 23	2.0	238	89	211	34	0.91	0.11	1.3	37
Arietids	May 29 to June 19	June 6	4.5	77	106	29	21	0.94	0.09	1.6	38
ζ - Perseids	June 1 to 16	June 6	3.0	78	--	59	4±2	0.79	0.35	1.6	29
β - Taurids	June 24 to July 5	June 28	2.0	276	162±4	246±4	9±4	0.86	0.36	2.5	31
δ - Aquarids	July 26 to Aug. 5	July 28	1.5	305	101±2	156±2	24±5	0.96	0.08	1.8	40
Perseids	July 15 to Aug. 18	Aug. 10 to 14	5.0	142	--	155	114	0.96	0.97	23	60
Orionids	Oct. 15 to 25	Oct. 20 to 23	1.2	29.3	103	87.8	163	0.92	0.54	6.32	66
Arietids, southern	Oct.1 to Nov.28	Nov. 5	1.1	27	150	122	6	0.85	0.30	1.91	28
Taurids, northern	Oct. 26 to Nov. 22	Nov. 10	0.4	221	160	308	2.5	0.86	0.31	2.16	29
Taurids, night	Nov.1 to Nov.30	Nov.15	1.0	220	160	300	3	0.86	0.3	2.1	37
Taurids, southern	Oct. 26 to Nov. 22	Nov. 5	0.9	45	157	112	5.1	0.85	0.36	2.39	28
Leonids southern	Nov. 15 to 20	Nov. 16 to 17	0.9	234	49	179	162	0.92	0.99	12.8	72
Bielids	Nov. 12 to 16	Nov. 14	0.4	250	109	223	13	0.76	0.88	3.6	16
Geminids	Nov. 25 to Dec. 17	Dec. 12 to 13	4.0	261	--	324	24	0.90	0.14	1.4	35
Ursids	Dec. 20 to 24	Dec. 22	2.5	270	--	210	56 ±3	1.0	0.92	--	37

(a) F_{max} = Ratio of maximum cumulative flux of stream to average cumulative sporadic flux



$$F = \frac{\textbf{CUMULATIVE FLUX OF STREAM}}{\textbf{AVERAGE CUMULATIVE SPORADIC FLUX}}$$

FIGURE F-6a: Activity Ratio Factor Versus Period of Activity (January-August) for Major Streams Based on Photographic Meteors with Mass, $m \geq 10^{-1}$ Gram



$$F = \frac{\text{CUMULATIVE FLUX OF STREAM}}{\text{AVERAGE CUMULATIVE SPORADIC FLUX}}$$

FIGURE F-6b: Activity Ratio Factor Versus Period of Activity (September-December) for Major Streams Based on Photographic Meteors with Mass, $m \geq 10^{-1}$ Gram

TABLE F-2

SPORADIC FLUX-MASS DATA FROM PENETRATION MEASUREMENTS

SPACECRAFT	SENSOR MATERIAL	K_1	SENSOR THICKNESS t (cm)	CHARACTERISTIC MASS m (gm)	CUMULATIVE FLUX N_{sp} (m^{-2} -sec^{-1})	LOG_{10} m (gm)	LOG_{10} N_{sp} (m^{-2} -sec^{-1})
PEGASUS I, II, III	ALUMINUM 2024 - T3	0.54	0.0406	5.20×10^{-7}	8.00×10^{-8}	-6.28	-7.10
			0.0203	7.25×10^{-8}	3.44×10^{-7}	-7.14	-6.46
EXPLORER XXIII	STAINLESS STEEL TYPE 302	0.32	0.0051	6.29×10^{-9}	3.33×10^{-6}	-8.20	-5.48
			0.0025	8.28×10^{-10}	5.68×10^{-6}	-9.08	-5.25
EXPLORER XVI	BERYLLIUM COPPER	0.30	0.0051	7.55×10^{-9}	2.66×10^{-6}	-8.12	-5.58
	BERYLCO NO. 25		0.0025	9.95×10^{-10}	5.16×10^{-6}	-9.00	-5.29

Flux-Mass Models

Average Total Ejecta Flux-Mass Model:

An average annual total cumulative flux-mass model for the lunar ejecta is to be used in preliminary design and is described as follows:

$0 \le V_{ej} \le 1.0$ $\qquad$ $\text{Log}_{10} N_{ej_t} = -10.75 - 1.2 \log_{10} m$

where

N_{ej_t} = number of ejecta particles of mass m or greater per square meter per second
m = particle mass in grams

The average ejecta velocity, 0.1 km/sec, is to be used with this distribution model.

Individual Ejecta Flux-Mass Model:

An average annual individual cumulative lunar ejecta flux-mass distribution for each of three velocity intervals should be used in detailed consideration of the ejecta hazard. These three distributions and the corresponding adopted ejecta velocity for each distribution are as follows:

* $0 \le V_{ej} \le 0.1$ $\qquad$ $\text{Log}_{10} N_{ej} = -10.79 - 1.2 \log_{10} m$

$V_{ej} = 0.1$ km/sec

$0.1 \le V_{ej} \le 0.25$ $\qquad$ $\text{Log}_{10} N_{ej} = -11.88 - 1.2 \log_{10} m$

$V_{ej} = 0.25$ km/sec

$0.25 \le V_{ej} \le 1.0$ $\qquad$ $\text{Log}_{10} N_{ej} = -13.41 - 1.2 \log_{10} m$

$V_{ej} = 1.0$ km/sec

*See Figure F-7.

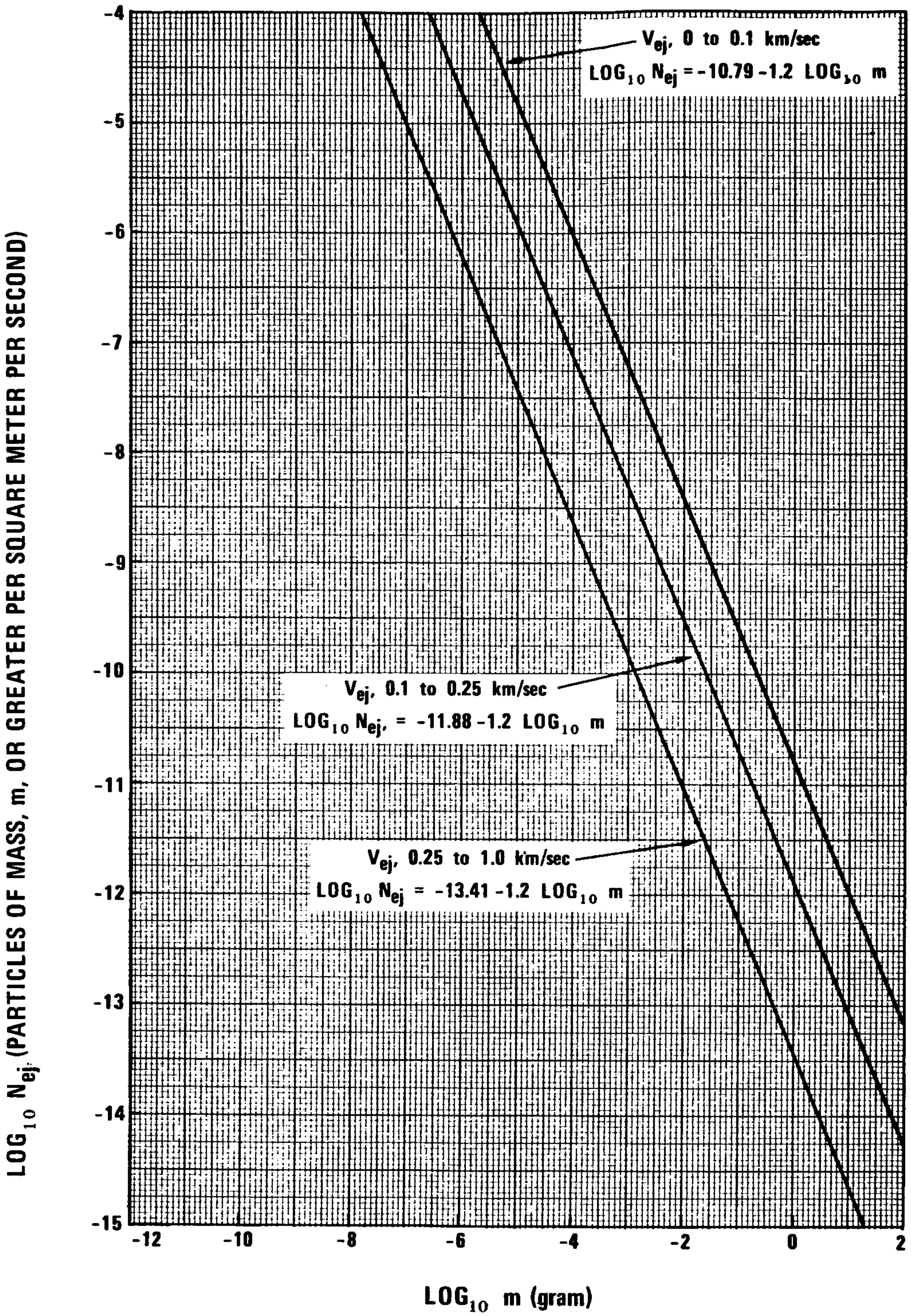


FIGURE F-7: Average Cumulative Lunar Ejecta Flux-Mass Distribution for Each of Three Ejecta Velocity Intervals

APPENDIX G

METABOLIC RATE CALCULATIONS AND MONITORING PROCEDURES

APPENDIX G

METABOLIC RATE CALCULATIONS AND MONITORING PROCEDURES

The three methods used to evaluate the metabolic rate of the crewmen during orbital and lunar surface extravehicular activities are listed below:

- Heart Rate Evaluator
- Oxygen Consumption Evaluator
- Liquid Cooling Garment Evaluator

A brief description of each metabolic rate evaluator was presented in Section 5.2.6 of this document. This Appendix is concerned with the monitoring process and calculations required to convert the raw computer and telemetry data into a metabolic rate.

Heart Rate to Metabolic Rate Real-Time Computation

Following ECG pulse detection by the computer and the filtering of the pulse through an automatic blanking loop which inhibits the counting of unwanted ECG event pulses, the computer is used as an event counter that registers the number of times the ECG pulse is set to the "on" condition within a 15 second period. The metabolic rate computation is obtained by actuating the appropriate computer control-start (C-Start). The output associated with 1-minute heart rate is processed through the linear regression equation:

$$\bar{E}_{H.R.} = m\,(H.R.) + b$$

where:

$\bar{E}_{H.R.}$	is the metabolic rate in Btu per hour
H.R.	is the heart rate in beats per minute
m	is the slope
b	is the ordinate

The values of m and b, obtained from baseline curves, are entered into the program manually and may be revised during the test. The 1-minute metabolic rate is updated every 15 seconds concurrent with the heart rate.

The duration (in milliseconds) of the computer blanking control for unwanted ECG pulses for various heart rates is summarized in Table G-1.

TABLE G-1: Computer Count Rejection Times

Beats/Min	Milliseconds
Greater than 180	300
161 to 180	320
141 to 160	340
121 to 140	360
101 to 120	380
91 to 100	400
81 to 90	420
80 or less	440

To determine the crewman's metabolic rate for a particular task, his heart rate is averaged over the time that the task is performed. This average is also processed through the linear regression curve of the equation above. A continuous summation of the total energy expended by the crewman is calculated as indicated in the equation below:

$$E_{H.R.} = \sum \frac{\bar{E}_{H.R.}}{240}$$

Since the energy rate computation $E_{H.R.}$ is updated every 15 seconds, the conversion to Btu is performed by dividing by 240.

Oxygen Consumption Method

Hand computation of the crewman's energy expenditure rate during extravehiular activity is determined from the life support system's oxygen bottle pressure. Because of the eight to fifteen psig random noise in the telemetry data, the oxygen method computation is not performed until a fifteen psig change occurs in the bottle pressure.

Equation (1) relates the change in oxygen bottle pressure to the energy expenditure rate:

$$(1) \quad \dot{E}O_2 = \left(\frac{\Delta O_2}{810}\right) \quad 6100 \quad \frac{(60)}{\Delta T} \quad - \quad L_S$$

where:

$\dot{E}O_2$ is the energy rate in Btu/hr.

ΔO_2 is the PLSS O_2 bottle pressure change in psig.

ΔT is the time duration in which the pressure change occurred in minutes.

810 is the conversion factor from psig to pounds at 70°F.

6100 is the conversion factor from pounds to Btu for a respiratory quotient of 0.8.

L_S is the suit leak rate in Btu/hr.

The suit pressure integrity check is monitored by the extravehicular mobility unit (EMU) systems personnel and the oxygen evaluator. As an example, the Apollo 12 EVA suit pressure telemetry data for both crewmen resulted in the following estimation of suit leakage:

	EVA-1		EVA-2	
	Integrity Check PSID/MIN	Leak Rate BTU/HR	Integrity Check PSID/MIN	Leak Rate BTU/HR
CDR	.13	105	.11	90
LMP	.14	115	.13	105

Equation (1) can then be reduced to the relation indicated in Equation (2):

$$(2) \quad \dot{E}O_2 = \left(\frac{\Delta O_2}{\Delta T}\right) 451.85 - L_S$$

The total energy expended for the entire EVA is calculated by converting the total oxygen bottle pressure change to Btu, taking into account the compressibility factor of oxygen at 900 psig as indicated in Equation (3):

$$(3) \quad EO_2 \text{ TOTAL} = \left[\left(\frac{\Delta O_2}{810}\right) 6100 - \left(L_S\right) \times \left(\Delta T\right)\right] 1.03$$

where:

EO_2 TOTAL is the energy expended in Btu.

ΔT is the total time of the EVA in hours.

1.03 is the adjustment of the compressibility factor of oxygen.

Computer processing of metabolic rate requires the implementation of the software oxygen filter which provides significant smoothing of the oxygen bottle pressure decay and provides realistic updates of metabolic rate at durations of the from four to ten minutes.

1. The program operation for the calculation of metabolic rate from the life support system oxygen bottle pressure decay is as follows:

$$(4)\quad \text{QMET } \emptyset 2 = \frac{\dot{\emptyset}2 \text{ FLOW RATE}}{\left[0.0001708 - \left(\frac{RQ-0.707}{0.293}\right) 1.23 \times 10^{-5}\right]} - L_S$$

where:

QMET Ø2 is the metabolic rate in Btu/hr.

Ø2 FLOW RATE is the oxygen flow rate in lbs/hr.

RQ is the respiratory quotient initially set to 0.9 by a Manual Entry Device (MED) input.

L_S is the suit leak rate in Btu/hr.

The denominator is the linear regression curve as a function of RQ for the conversion from oxygen in pounds to Btu.

2. The total metabolic expenditure based upon oxygen bottle pressure decay computed as follows:

$$(5)\quad \text{QMET } \emptyset 2 \text{ (TOTAL)} = \frac{\sum \text{QMET } \emptyset 2 \left[(\text{GET})_R - (\overline{\text{GET}})\right]}{3600} \quad \text{Equation (5)}$$

where:

QMET Ø2 (TOTAL) is the summation of QMET Ø2 converted to Btu.

$(\text{GET})_R - (\overline{\text{GET}})$ is the QMET Ø2 update time in integer seconds.

The interval over which QMET Ø2 (TOTAL) is summed is determined by the activation of the PBI start/stop button.

3. The oxygen flow rate is computed as follows:

$$(6) \quad \text{Ø2 FLOW RATE} = \frac{1.22 \times 10^{-3} \ (P_R - \overline{P}) \ (3600)}{(GET)_R - (\overline{GET})}$$

where:

P_R is the oxygen reference pressure at time $(GET)_R$

$\overline{P}$ is the average of the oxygen pressure for n samples over ten seconds.

4. Method for oxygen flow rate computation -- The O_2 Software Filter:

a. Subsequent to activation of the metabolic rate program, the first ten (10) seconds of data are averaged, and a reference pressure P_R is established. $(GET)_R$ is the ground elapsed time at last data value.

b. $\overline{P}$ is computed at ten (10) second intervals thereafter, as follows:

$$(7) \qquad \overline{P} = \frac{P_1 + P_2 + \ldots Pi + \ldots Pn}{n} = \frac{\sum O_2 \text{ Pressure}}{\text{Number of Samples}}$$

An individual data value Pi will be average in $\overline{P}$ if

$$\left| P_R - Pi \right| < K_{P_\delta}$$

where:

K_{P_δ} is the acceptable data band width in psia, psa MED input in psia.

K being set to 3 for optimum results as determined by the Apollo 9 EVA.

$(\overline{GET})$ is the ground elapsed time at the last data value in the $\overline{P}$ computation.

c. The flow rate computation equation EQ(6) is made if $(P_R - \overline{P}) \geq P_\delta$.

where:

P_δ is a MED input initially set to 15 psia.

If $(P_R - \overline{P}) < P_\delta$, continue to sample for the next 10 seconds and determine a new $\overline{P}$.

d. If Ø2 FLOW RATE < 0.66 lbs/hr, the metabolic rate computation of EQ(4) is performed.

   If Ø2 FLOW RATE $\geq$ 0.66 lbs/hr, the oxygen pressure should continue to be sampled for the next 10 seconds to determine a new $\overline{P}$.

e. After an Ø2 FLOW RATE Equation (6) has been computed, which results in a value less than 0.66 lbs/hr, the reference pressure P_R must be replaced by the value of $\overline{P}$ and $(GET)_R$ by (GET), and the calculations for new Ø2 FLOW RATE should also continue.

During lunar surface activity, hand calculations of the metabolic rate were performed primarily to verify the correctness of the computer updates. All metabolic rates were computed from the feed-water-on time to cabin repressurization. For determining the space suit leak rate, calculations from an Apollo 12 EVA suit are presented below:

1. General Equation of State

$$PV = MRT$$

where:

P = Pressure psig

V = Volume in cubic ft

R = Gas constant 48.24 ft-lb/lb-R° for oxygen

T = Temperature °R

M = Mass pounds (lbs)

2. Specific Calculation

   During pre-EVA activity, the EMU pressure check provides a suit leakage data point in psid/min. The objective of the suit leak rate calculation is to convert this data point to an estimated leak in Btu.

Assuming a suit volume of 1 cubic foot and a temperature of 70°F.:

$$M_{8.88} = \frac{(1)\ (144)\ (60)\ P}{(48.24)\ (530)} = \frac{8640}{25,567}\ P = 0.3379P$$

where:

$M_{8.88}$ is the mass rate in lbs/hr.

From empirical data and from various theoretical considerations, the leak rate for a suit pressure of 3.88 psia over vacuum is assumed to be 1/2.5 times the leak rate for a suit pressure of 8.88 psia over 5 psia. Then:

$$M_{3.88} = \frac{M_{8.88}}{2.5} = \frac{.3379P}{2.5} = 0.13516P$$

The leak rate L_s in Btu/hr is thus:

$$L_s = (M_{3.88})\ (6100\ \text{Btu/lb}) = (0.1351P)\ (6100)$$

3. Computation for the Apollo 12 EVA Space Suit Leak Rate

EVA-1

CDR P = .13 psid/min

L_s = (.1351) (.13) (6100) = 107 Btu/hr

LMP P = .14 psid/min

L_s = (.1351) (.14) (6100) = 115 Btu/hr

EVA-2

CDR P = .11 psid/min

L_s = (.1351) (.11) (6100) = 91 Btu/hr

LMP P = .13 psid/min

L_s = (.1351) (.13) (6100) = 107

Total Metabolic Expenditure Calculations

The total metabolic expenditure is found from the following equation:

$$EO_2 = \left[\left(\frac{\Delta O_2}{810}\right) (6100) + 260 - L_s (\Delta T)\right] 1.03$$

where:

EO_2 is the total energy expended in Btu.

ΔO_2 is the total O_2 usage over the entire EVA.

810 is the conversion from psig to pounds.

6100 is the conversion from pounds to Btu.

260 is the additional Btu usage from "O_2 regulator on" to beginning of liquid cooling or "feedwater valve to run".

L_s is the suit leak rate in Btu/hr.

ΔT is the time duration for the entire EVA.

1.03 adjustment for the compressibility factor of oxygen @ 900 psig.

Liquid Cooling Garment Method

The liquid cooling garment metabolic rate is predicted from telemetry data on the water inlet temperature and the change in temperature across the LCG. The method makes an initial estimate of the metabolic rate, based on an empirical linear relationship between heat removal by the LCG and the total metabolic rate. Then the inlet temperature is used in combination with the heat-balance equations to estimate the sweat rate, and the final estimate of metabolic rate is determined by using an empirical input command. The process for the LCG metabolic rate determination through monitoring, telemetry data is as follows.

The computer calculations can be altered by changing the program inputs for the heat exchange between the inside and the outside of the suit or by changing the factor instruction (Fac) in the program to different levels of sensitivity. The Fac is varied in three ways:

1. The initial input for Fac is "0", which programs calculations for a less sensitive, but more stable, prediction. It is used during transient modes such as diverter valve changes.

2. The Fac input of "1" programs calculations for a more sophisticated prediction. It is used when there are no significant changes in LCG ΔT or inlet temperature for a 20 minute period.

3. If the heat removal (ΔT) exceeds a preset value (greater than 7.5°F), the input for Fac will be changed from 0 or 1 to a range of 2.3 to 2.7, depending upon the value of ΔT. In this case, the final predicted metabolic rate is replaced by an alternate estimation of the rate which combines the heat pickup to the LCG with a nominal sweat rate.

As a guide to the selection of the Fac input, the metabolic rate predictions should be most reliable when the system is functioning within the prescribed limits for Fac = 1. The predictions should be less reliable when Fac = 0 and should be less reliable when Fac is varied between 2.3 and 2.7.

A monitor records the time when a diverter valve change occurs. The valve change is noted by rapid changes in the LCGΔT and the inlet water temperature. The monitor notes any rapid changes in these parameters which do not appear to be associated with a change in the diverter valve position. The monitor introduces a Fac change to 0 (if Fac = 1), after any rapid change in ΔT or inlet temperature. The LCG inlet temperature, the LCGΔT, and the metabolic rate and cumulative metabolic expenditures are recorded at 6-minute intervals referenced from the program start.

The monitor introduces a Fac input change if no significant changes in LCGΔT or in inlet temperature occur during a 20 minute period. If the ΔT was greater than 7.5°F, the Fac change should be as follows:

ΔT, °F	Fac input
7.5	2.3
8.0	2.3
8.5	2.4
9.0	2.5
9.5	2.6
10.0	2.7

The Fac setting is checked frequently for the adequacy of setting.

The monitor is required to frequently verify the computer program results by use of the prediction chart shown in Figure G-1. With a Fac setting of 0, the metabolic rate can be estimated from the telemetered ΔT value by reading across the graph to the comfort line. With a Fac setting of 1, the rate is estimated from the telemetered ΔT value by reading across the graph to the appropriate inlet temperature line.

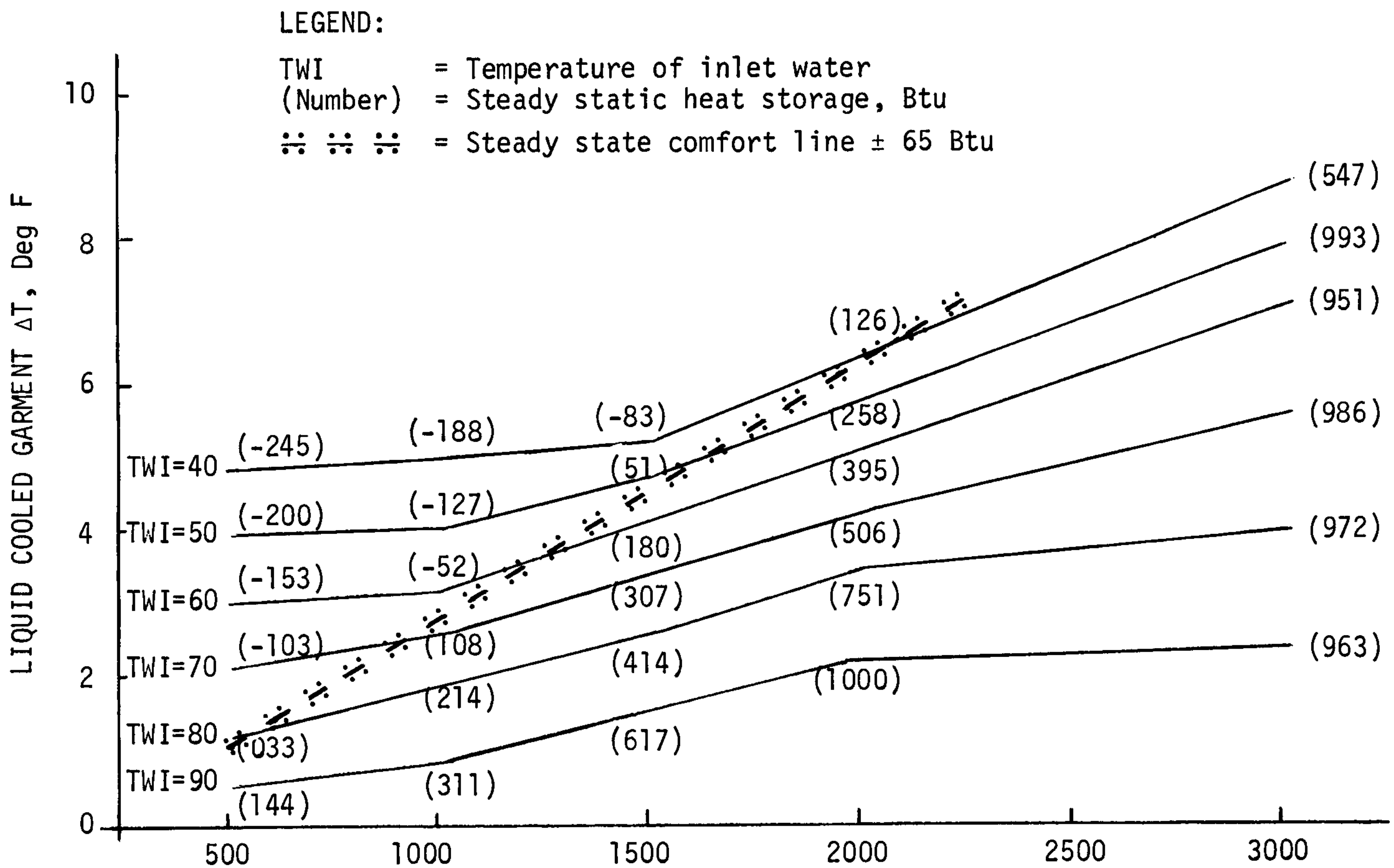


FIGURE G-1: Metabolic Rate Prediction Chart

APPENDIX H

DEFINITIONS, CONVERSION FACTORS, AND PHYSICAL CONSTANTS

APPENDIX H

DEFINITIONS, CONVERSION FACTORS, AND PHYSICAL CONSTANTS

This appendix presents definitions, conversion factors, and physical constants that may be useful as reference data to the EVA system designer. Section 1.0 includes standard measurement units, constants, and definitions from the engineering and biomedical fields derived from various aerospace documents.

Section 2.0 contains conversion factors and standard metric and engineering units derived from the Compendium of Human Responses to the Aerospace Environment, Lovelace Foundation, 1968. In using the conversion tables, the reader may convert from the measure of quantities in the units listed on the left to those across the top of the table by multiplying by the factor given in the intersecting cell. The superscripted member to the right of each cell entry is the power of ten by which the factor is to be multiplied. For example, 8.68977^{-2} is equivalent to 0.0868977. Underscored values are exact quantities.

Section 3.0 presents attitude information which may be useful in interpreting atmospheric data. Pressure and temperature values are given for selected altitudes.

ALBEDO:
The per cent of diffused reflection of "white light" for a given surface.

ATOMIC MASS UNIT (amu):
Atomic mass unit (defined as: 16 amu = the atomic mass of the most abundant isotope of oxygen).

ATMOSPHERE (atm):
The pressure exerted by 76 cm mercury with a density of 13.5951 gm/cm^3 at 1 g (the standard barometric pressure at sea level).

1 atm = 1.01325×10^6 dynes/cm^2
= 1033.2 gm/cm^2
= 760 mm Hg
= 14.696 psi

BRITISH THERMAL UNIT (Btu):

1 Btu = 1.0559×10^{10} ergs
= 251.995 gm-cal
= 778.77 ft-lbs
= 0.25199 kcal
1 Btu/hr = 0.1667 Btu/min
= 0.04199 kcal/min
= 0.2932 watt
1 Btu/min = 0.25199 kcal/min
= 0.023599 hp
= 17.595 watts
1 Btu/ft^2, hr = 2.7125 kcal/m^2, hr

BTPS:
Body Temperature (=37° C), ambient Pressure, and Saturated (water vapor pressure = 47 mm Hg).

CALORIC EQUIVALENT OF OXYGEN:
One liter of oxygen (STPD) consumed is equivalent to 4.825 kcal of metabolic heat produced, when the R.Q. is 0.82.

CANDLE (c):
The unit of luminous intensity.
1 candle = 1 lumen/steradian

CENTIMETER (cm):

1 cm = 0.03280 ft
= 0.3937 in
= 0.01 m
= 10 mm
= 1×10^4 μ

(See also Square Centimeter, Cubic Centimeter).

CENTIMETER-CANDLE (phot):
1 phot = 1×10^4 lux

CENTIMETERS PER SECOND PER SECOND:
1 cm/sec^2 = 0.0328 ft/sec^2

CENTIPOISE:
Unit of absolute viscosity.
1 centipoise = 0.01 poise

CLO (clo):
The unit of insulation resistance for clothing.

1 clo = 0.18 °C m^2hr/kcal
= 0.88 °F ft^2hr/Btu

CUBIC CENTIMETER (cc or cm^3):

1 cc = 3.531×10^{-5} ft^3
= 0.061023 in^3
= 1×10^{-6} m^3
= 1000 mm^3
= 2.6417×10^{-4} gal (US fluid)
= 0.0338 oz (US fluid)
= 2.113×10^{-3} pint (US liquid)
1 cc/sec = 0.0021186 ft^3/min

CUBIC FOOT:

1 ft^3 = 1728 in^3
= 28.32 liters
= 0.02832 m^3
1 ft^3/min = 472.0 cc/sec
= 0.4720 liter/sec
= 62.43 lbs H_2O/min
1 ft^3/sec = 1699.3 liters/min

CUBIC FOOT:

1 ft^3 = 1728 in^3
= 28.32 liters
= 0.02832 m^3
1 ft^3/min = 472.0 cc/sec
= 0.4720 liter/sec
= 62.43 lbs H_2O/min
1 ft^3/sec = 1699.3 liter/min

CUBIC INCH:

1 in^3 = 5.787×10^{-4} ft^3
= 1.639×10^{-2} liter
= 1.639×10^{-5} m^3

CUBIC METER:

1 m^3 = 35.3144 ft^3
= 6.1023×10^4 in^3
= 999.973 liters

DECIBEL (db):
Used for comparing power levels, acoustical or electrical.

1 db = 10 $\log_{10} P/P_0$ where P is the power to be compared to a reference power P_0
= 1 bel = increase in power (P) by a factor of 10

(See also Sound Pressure Level).

DEGREE (ANGULAR) (deg):

1 deg = 60 minutes
= 0.01745 radian
= 3600 seconds
1 deg^2 = 3.0462×10^{-2} steradian

DEGREES CENTIGRADE (°C):

°C = 5/9 (°F - 32)
1 °C = 1.8 °F

DEGREES FAHRENHEIT (°F):
°F = (9/5 × °C) + 32
1 °F = 0.556 °C

DEGREES PER SECOND:
1 deg/sec = 0.017453 radian/sec
= 0.1667 rpm

DYNE (dyne):
1 dyne = 1.0197×10^{-6} kg
= 2.2481×10^{-6} lb
1 dyne-cm = 1 erg

DYNE-SECOND PER SQUARE CENTIMETER:
Unit of viscosity. (See Poise).

DYNE PER SQUARE CENTIMETER:
1 dyne/cm^2 = 9.8692×10^{-7} atm
= 0.0010197 gm/cm^2
= 4.0148×10^{-4} in H_2O
= 7.5006×10^{-4} mm Hg
= 1.4504×10^{-5} psi

ELECTRON CHARGE (e):
e = 1.602×10^{-19} coulomb

ERG (erg):
1 erg = 9.4805×10^{-11} Btu
= 7.3756×10^{-8} ft-lb
= 2.3889×10^{-11} kcal
= 8.8510×10^{-7} lb-in

FOOT (ft):
1 ft = 30.48 cm
= 12 in
= 0.3048 m
(See also Square Foot, Cubic Foot).

FOOT-CANDLE (ft-c):
1 ft-c = 1 lumen/ft^2
= 10.764 lumen/m^2

FOOT-LAMBERT (ft-L):
1 ft-L = 1.0764 millilamberts

FOOT PER MINUTE:
1 ft/min = 0.3048 m/min
= 0.005080 m/sec
= 0.011364 mph

FOOT PER SECOND:
1 ft/sec = 1.0973 km/hr
= 0.5921 knot (per hr)
= 0.6818 mph

FOOT-POUND (ft-lb):
1 ft-lb = 0.001285 Btu
= 1.3558×10^{7} ergs
= 3.2389×10^{-4} kcal
1 ft-lb/min = 3.0303×10^{-5} hp
= 0.01667 ft-lb/sec
= 0.022597 watt
1 ft-lb/sec = 0.001818 hp
= 0.01943 kcal/min
= 1.3558 watts

G (g):
The acceleration of gravity (also the acceleration of a vehicle).
1 g = 32.174 ft/sec^2
= 980.665 cm/sec^2

G (G):
The unit of force causing displacement of organs and fluids in the body when the body is accelerated, where 1 G = force per unit mass due to acceleration of 1 g.

GRAM (gm):
1 gm = 0.001 kg
= 1000 mg
= 0.03527 oz
= 0.0022046 lb
1 gm/cm^3 = 62.428 lbs/ft^3
1 gm/hr = 0.540 lb/day
= 0.0003757 lb/min
1 gm/liter = 0.062427 lb/ft^3
1 gm/cm^2 = 9.6784×10^{-4} atm
= 980.665 dynes/cm^2
= 0.9356 mm Hg
= 0.014223 psi
1 gm/m^2, hr = 2.78×10^{-5} gm/cm^2, sec
= 0.7448 lb/ft^2, hr

GRAM-CALORIE (gm-cal):

1 gm-cal = 3.0874 ft-lbs
= 0.001 kcal

HEMATOCRIT:
The height of the column of red blood cells in a tube of whole blood which has settled or has been centrifuged to separate cells from plasma. Usually expressed in per cent.

HORSEPOWER (hp):
1 hp = 3.300×10^{4} ft-lbs/min
= 550 ft-lbs/sec
= 10.688 kcal/min
= 745.7 watts

INCH (in):
1 in = 2.540 cm
= 0.0833 ft
= 25.40 mm
(See also Cubic Inch, Square Inch)

INCH OF WATER (in H_2O)
1 in H_2O = 0.002458 atm
(at 4° C) = 2490.82 dynes/cm^2
= 0.0361 psi
= 1.868 mm Hg

JOULE (joule)
1 joule = 1 watt-sec

KILOGRAM (kg):
1 kg = 1000 gm
= 2.205 lb
= 32.1507 oz

KILOGRAM-CALORIE (kcal or large Calorie):
1 kcal = 3.9683 Btu
= 4.186×10^{10} ergs
= 1000 gm-cal
= 3087 ft-lbs
1 kcal/hr = 0.0661 Btu/min
= 0.857 ft-lbs/sec
= 0.1667 kcal/min
= 1.161 watts
1 kcal/m^2 hr = 0.3687 Btu/ft^2 hr
1 kcal/min = 3.9685 Btu/min
= 51.457 ft-lbs/sec
= 0.093557 hp
= 69.767 watts

KILOGRAM-CENTIMETER SQUARED:
1 kg-cm^2 = 0.3417 lb-in^2

KILOGRAM-METER PER SECOND:
1 kg-m/sec = 7.2330 ft-lb/sec
= 9.80665 watts

KILOMETERS PER HOUR:
1 km/hr = 0.9113 ft/sec
= 0.5396 knot
= 0.6214 mph

KNOT (nautical mile):
1 knot = 1.689 ft/sec
= 1.853 km/hr
= 1.1516 mph

LAMBERT (L):
Unit of surface brightness.
1 L = 0.3183 c/cm^2
= 2.0536 c/in^2
= 1 lumen/cm^2

LITER (l):
1 liter = 0.03531 ft^3
= 61.02 in^3
= 1000 ml
1 liter/min = 5.886×10^{-4} ft^3/sec
1 liter/sec = 2.12 ft^3/min

LUMEN (lumen):
1 lumen = 0.001496 watt
= 0.07958 spherical candle power
1 lumen/ft^2 = 1 ft-c
= 10.764 lumen/m^2

LUX:
(See Meter-Candle).

METER (m):
1 m = 100 cm
= 3.281 ft
= 39.37 in
(See also Cubic Meter).

METER-CANDLE (lux):
1 lux = 1 lumen/m^2
= 0.092903 ft-c

METER PER SECOND (m/sec):
1 m/sec = 3.281 ft/sec
= 3.600 km/hr
= 2.2369 mph

MICRON (μ or mu):
1μ = 10^{-6} meter
= 3.937×10^{-5} in
= 0.001 mm

MIL (mil):
1 mil = 0.001 in
= 0.0254 mm
= 25.40μ

MILES PER HOUR (mph):
1 mph = 88 ft/min
= 1.4667 ft/sec
= 1.6093 km/hr
= 0.8684 knot

MILLIGRAM (mg):
1 mg = 0.001 gm
= 3.5274 oz
= 2.2046×10^{-6} lb
1 mg/m^3 = 6.243×10^{-4} lb/ft^3

MILLILAMBERT (mL):
1 mL = 0.929 lumen/ft^2
(perfectly diffused light)

MILLILITER (ml):
1 ml = 1.000028 cc
= 0.061025 in^3
= 0.001 liter
= 0.0338 oz (US, fluid)

MILLILITERS PER HOUR:
1 ml/hr = 0.06102 in^3/hr

MILLIMETER (mm):
1 mm = 0.10 cm
= 0.03937 in
= 1000μ
(See also Square Millimeter).

MILLIMETER OF MERCURY (mm Hg):
1 mm Hg = 0.0013158 atm
(at 0° C) = 1333.22 dyne/cm^2
= 1.3595 gm/cm^2
= 0.019337 psi
= 0.535 in H_2O

MILLIREM (millirem):
1 millirem = 10^{-3} rem
(roentgen equivalent man)

MILLISECONDS (msec):
1 msec = 0.001 sec

OUNCE (oz):
1 oz = 28.3495 gm
= 0.0625 lb

OXYGEN SATURATION:
The ratio of the volume of oxygen (at STP) in a given unit volume of blood, to the maximum volume of O_2 that can be absorbed by that unit volume of blood at high partial pressures of O_2 (e.g. 760 mm Hg); usually expressed in per cent.

PARTS PER MILLION (ppm):
1 ppm = 1.0 mg/liter of H_2O
= 8.345 lbs/million gallons

PHON (phon):
1 phon unit = SPL of a 1000 cycle/sec tone

PHOT:
(See Centimeter Candle).

POISE:
Unit of viscosity.
1 poise = 1 dyne/sec, cm^2
= 1 gm/cm, sec
= 0.067196 lb/ft, sec

POUND (lb);
1 lb = 453.5924 gm
= 0.45359 kg
= 16 oz
1 lb/day = 18.89 gm/hr
1 lb/hr = 0.7559 gm/min
= 10.886 kg/day

POUND-INCH (lb—in):
1 lb-in = 1.1298×10^6 dyne/cm

POUND-INCH SQUARED:
Unit of moment of inertia.
1 lb-in^2 = 2.9264 kg-cm^2

POUND OF WATER PER MINUTE (lb H_2O/min):
1 lb H_2O/min = 0.01603 ft^3/min
= 2.670×10^{-4}/ft^3/sec

POUND PER CUBIC FOOT (lb/ft^3):
1 lb/ft^3 = 0.01602 gm/cm^3

POUNDS PER SQUARE INCH (psi):
1 psi = 0.06805 atm
= 6.8947×10^4 dyne/cm^2
= 70.307 gm/cm^2
= 51.715 mm Hg
= 27.7 in H_2O

POUNDS PER SQUARE INCH ABSOLUTE (psia):
Absolute pressure, where 0 psia = vacuum

POUND WEIGHT (lb wt):
1 lb wt = 4.4482×10^5 dynes
= 453.59 gm wt

RAD (rad):
Radiation absorbed dose.

RADIAN (rad):
1 radian = $\frac{1}{2\pi}$ circumference or revolution (0.15915)
= 57.296 deg
1 radian/sec = 57.296 deg/sec
= 9.549 rpm
1 radian/sec^2 = 572.96 rpm^2

RBE:
Relative biological effectiveness.

RELATIVE HUMIDITY:
The ratio of the quantity of water vapor in an atmosphere to the quantity which would saturate at the existing temperature. Also the ratio of pressure of water vapor to saturation pressure at that temperature.

REM:
Roentgen equivalent man.

RESPIRATORY QUOTIENT (R.Q.):
The ratio of the rate of production of carbon dioxide (volume at STP per unit time) to the rate of uptake of oxygen (volume at STP per unit time).

REVOLUTIONS PER MINUTE (rpm):
1 rpm = 6 deg/sec
= 0.10472 radian/sec
1 rpm^2 = 0.001745 radian/sec^2

ROENTGEN (r):
1 r = ionization by X or γ-rays producing 1 electrostatic unit of charge in 1 cm^3 of air (STP)
= 83.0 ergs/gm

ROOT MEAN SQUARE (rms):
Square root of the mean of the squares of a set of numbers.

SONE:
Related to phon logarithmically.

SOUND PRESSURE LEVEL (SPL):
SPL is sound pressure related logarithmically to a reference level of pressure (P_0). which by convention is 0.0002 dynes/cm^2. The defining equation is:
SPL = $20 \log_{10} P/P_0$ in decibels

SQUARE CENTIMETER (cm^2):
1 cm^2 = 1.076×10^{-3} ft^2
= 0.1550 in^2
= 100 mm^2

SQUARE FOOT (ft^2):
1 ft^2 = 929.0 cm^2
= 144 in^2

SQUARE INCH (in^2):
1 in^2 = 6.4516 cm^2
= 0.006944 ft^2
= 645.1626 mm^2

SQUARE MILLIMETER (mm^2):
1 mm^2 = 0.01 cm^2
= 0.001550 in^2

STANDARD DEVIATION (S. D.)
The square root of the average of the squares of deviation from the mean. Also called root mean square deviation. Same as **Standard Error**.

STERADIAN (steradian):
$\frac{1}{4\pi}$ solid angle around a point.
1 steradian = 3282.8063 deg^2
= 0.07958 sphere

STANDARD TEMPERATURE AND PRESSURE, DRY (STPD):
0° C, 760 mm Hg, water vapor pressure = 0.

WATT (watt):
1 watt = 1 joule/sec
= 1×10^7 erg/sec
= 0.7376 ft-lb/sec
= 0.001341 hp
= 0.01432 kcal/min

SPECIALIZED CONVERSION FACTORS

	Å	cm	ft	in.	km	m	μ	mils	miles (US)	mm	miles (Nautical)	rods	yd
Angstrom Units	1.00000	1.00000^{-8}	3.28084^{-10}	3.93701^{-9}	1.00000^{-13}	1.00000^{-10}	1.00000^{-4}	3.93701^{-6}	6.21371^{-14}	1.00000^{-7}	5.39957^{-14}	1.98839^{-11}	1.09361^{-10}
Centimeters	1.00000^{8}	1.00000	3.28084^{-2}	3.93701^{-1}	1.00000^{-5}	1.00000^{-2}	1.00000^{4}	3.93701^{2}	6.21371^{-6}	1.00000^{1}	5.39957^{-6}	1.98839^{-3}	1.09361^{-2}
Feet	3.04800^{9}	3.04800^{1}	1.00000	1.20000^{1}	3.04800^{-4}	3.04800^{-1}	3.04800^{5}	1.20000^{4}	1.89394^{-4}	3.04800^{2}	1.64579^{-4}	6.06061^{-2}	3.33333^{-1}
Inches	2.54000^{8}	2.54000	8.33333^{-2}	1.00000	2.54000^{-5}	2.54000^{-2}	2.54000^{4}	1.00000^{3}	1.57828^{-5}	2.54000^{1}	1.37149^{-5}	5.05050^{-3}	2.77778^{-2}
Kilometers	1.00000^{13}	1.00000^{5}	3.28084^{3}	3.93701^{4}	1.00000	1.00000^{3}	1.00000^{9}	3.93701^{7}	6.21371^{-1}	1.00000^{6}	5.39957^{-1}	1.98839^{2}	1.09361^{3}
Meters	1.00000^{10}	1.00000^{2}	3.28084	3.93701^{1}	1.00000^{-3}	1.00000	1.00000^{6}	3.93701^{4}	6.21371^{-4}	1.00000^{3}	5.39957^{-4}	1.98839^{-1}	1.09361
Microns	1.00000^{4}	1.00000^{-4}	3.28084^{-6}	3.93701^{-5}	1.00000^{-9}	1.00000^{-6}	1.00000	3.93701^{-2}	6.21371^{-10}	1.00000^{-3}	5.39957^{-10}	1.98839^{-7}	1.09361^{-6}
Mils	2.54000^{5}	2.54000^{-3}	8.33333^{-5}	1.00000^{-3}	2.54000^{-8}	2.54000^{-5}	2.54000^{1}	1.00000	1.57828^{-8}	2.54000^{-2}	1.37149^{-8}	5.05050^{-6}	2.77778^{-5}
Miles (US)	1.60934^{13}	1.60934^{5}	5.28000^{3}	6.33600^{4}	1.60934	1.60934^{3}	1.60934^{9}	6.33600^{7}	1.00000	1.60934^{6}	8.68977^{-1}	3.20000^{2}	1.76000^{3}
Millimeters	1.00000^{7}	1.00000^{-1}	3.28084^{-3}	3.93701^{-2}	1.00000^{-6}	1.00000^{-3}	1.00000^{3}	3.93701^{1}	6.21371^{-7}	1.00000	5.39957^{-7}	1.98839^{-4}	1.09361^{-3}
Miles(Nautical)	1.85200^{13}	1.85200^{5}	6.07612^{3}	7.29134^{4}	1.85200	1.85200^{3}	1.85200^{9}	7.29134^{7}	1.15078	1.85200^{6}	1.00000	3.68250^{2}	2.02537^{3}
Rods	5.02920^{10}	5.02920^{2}	1.65000^{1}	1.98000^{2}	5.02920^{-3}	5.02920	5.02920^{6}	1.98000^{5}	3.12500^{-3}	5.02920^{3}	2.71555^{-3}	1.00000	5.50000
Yards	9.14400^{9}	9.14400^{1}	3.00000	3.60000^{1}	9.14400^{-4}	9.14400^{-1}	9.14400^{5}	3.60000^{4}	5.68182^{-4}	9.14400^{2}	4.93737^{-4}	1.81818^{-1}	1.00000

1. LENGTH

SPECIALIZED CONVERSION FACTORS

	Acre	in. (Circular)	Mil (Circular)	cm^2	ft^2	in^2	m^2	mm^2	Rod^2	$Yard^2$
Acre	1.00000	7.98657^{6}	7.98657^{12}	4.04686^{7}	4.35600^{4}	6.27264^{6}	4.04686^{3}	4.04686^{9}	1.60000^{2}	4.84000^{3}
Circular inch	1.25211^{-7}	1.00000	1.00000^{6}	5.06707	5.45415^{-3}	7.85398^{-1}	5.06707^{-4}	5.06707^{2}	2.00336^{-5}	6.06017^{-4}
Circular mil	1.25211^{-13}	1.00000^{-6}	1.00000	5.06707^{-6}	5.45415^{-9}	7.85398^{-7}	5.06707^{-10}	5.06707^{-4}	2.00336^{-11}	6.06017^{-10}
Centimeter^2	2.47105^{-8}	1.97353^{-1}	1.97353^{5}	1.00000	1.07639^{-3}	1.55000^{-1}	1.00000^{-4}	1.00000^{2}	3.95368^{-6}	1.19598^{-4}
Feet^2	2.29568^{-5}	1.83347^{2}	1.83347^{8}	9.29030^{2}	1.00000	1.44000^{2}	9.29030^{-2}	9.29030^{4}	3.67310^{-3}	1.11111^{-1}
Inch^2	1.59423^{-7}	1.27324	1.27324^{6}	6.45160	6.94444^{-3}	1.00000	6.45160^{-4}	6.45160^{2}	2.55076^{-5}	7.71605^{-4}
Meter^2	2.47105^{-4}	1.97353^{3}	1.97353^{9}	1.00000^{4}	1.07639^{1}	1.55000^{3}	1.00000	1.00000^{6}	3.95368^{-2}	1.19598
Millimeter^2	2.47105^{-10}	1.97353^{-3}	1.97353^{3}	1.00000^{-2}	1.07639^{-5}	1.55000^{-3}	1.00000^{-6}	1.00000	3.95368^{-8}	1.19598^{-6}
Rod^2	6.25000^{-3}	4.99161^{4}	4.99161^{10}	2.52928^{5}	2.72250^{2}	3.92040^{4}	2.52928^{1}	2.52928^{7}	1.00000	3.02500^{1}
Yard^2	2.06611^{-4}	1.65012^{3}	1.65012^{9}	8.36127^{3}	9.00000	1.29600^{3}	8.36127^{-1}	8.36127^{5}	3.30578^{-2}	1.00000

2. AREA

SPECIALIZED CONVERSION FACTORS

	Centimeter^3	Feet^3	Gallon	Inch^3	Liter	Meter^3	Yard^3
Centimeter^3	$\underline{1.00000}$	3.53146^{-5}	2.64171^{-4}	6.10236^{-2}	9.99972^{-4}	$\underline{1.00000}^{-6}$	1.30794^{-6}
Feet^3	2.83168^{4}	$\underline{1.00000}$	7.48052	$\underline{1.72800}^{3}$	2.83161^{1}	2.83168^{-2}	3.70370^{-2}
Gallon (U.S.)	3.78543^{3}	1.33680^{-1}	$\underline{1.00000}$	$\underline{2.31000}^{2}$	3.78533	3.78543^{-3}	4.95113^{-3}
Inch^3	1.63871^{1}	5.78704^{-4}	4.32900^{-3}	$\underline{1.00000}$	1.63866^{-2}	1.63871^{-5}	2.14335^{-5}
Liter	1.00003^{3}	3.53156^{-2}	2.64178^{-1}	6.10253^{1}	$\underline{1.00000}$	1.00003^{-3}	1.30798^{-3}
Meter^3	$\underline{1.00000}^{6}$	3.53146^{1}	2.64171^{2}	6.10236^{4}	9.99972^{2}	$\underline{1.00000}$	1.30794
Yard^3 (U.S.)	7.64554^{5}	$\underline{2.70000}^{1}$	2.01974^{2}	$\underline{4.66560}^{4}$	7.64538^{2}	7.64554^{-1}	$\underline{1.00000}$

3. VOLUME

SPECIALIZED CONVERSION FACTORS

	Grain	$Gram_m$	$Kilogram_m$	Ounce (avdp)	$Pound_{mass}$	Slug	Ton (short)
Grain	$\underline{1.00000}$	6.47988^{-2}	6.47988^{-5}	2.28571^{-3}	1.42857^{-4}	4.44012^{-6}	7.14285^{-8}
$Gram_{mass}$	1.54323^{1}	$\underline{1.00000}$	$\underline{1.00000}^{-3}$	3.52739^{-2}	2.20462^{-3}	6.85216^{-5}	1.10231^{-6}
$Kilogram_{mass}$	1.54323^{4}	$\underline{1.00000}^{3}$	$\underline{1.00000}$	3.52739^{1}	2.20462	6.85216^{-2}	1.10231^{-3}
Ounce (avdp)	$\underline{4.37500}^{2}$	2.83495^{1}	2.83495^{-2}	$\underline{1.00000}$	6.25000^{-2}	1.94256^{-3}	3.12500^{-5}
$Pound_{mass}$	$\underline{7.00000}^{3}$	4.53592^{2}	4.53592^{-1}	$\underline{1.60000}^{1}$	$\underline{1.00000}$	3.10809^{-2}	$\underline{5.00000}^{-4}$
Slug	2.25218^{5}	1.45939^{4}	1.45939^{1}	5.14785^{2}	3.21740^{1}	$\underline{1.00000}$	1.60870^{-2}
Ton (short)	$\underline{1.40000}^{7}$	9.07184^{5}	9.07184^{2}	$\underline{3.20000}^{4}$	$\underline{2.00000}^{3}$	6.21618^{1}	$\underline{1.00000}$

4. MASS

SPECIALIZED CONVERSION FACTORS

	Day	Hour	Microsecond	Millisecond	Minute	Second
Day	$\underline{1.00000}$	$\underline{2.40000}^{1}$	$\underline{8.64000}^{10}$	$\underline{8.64000}^{7}$	$\underline{1.44000}^{3}$	$\underline{8.64000}^{4}$
Hour	4.16666^{-2}	$\underline{1.00000}$	$\underline{3.60000}^{9}$	$\underline{3.60000}^{6}$	$\underline{6.00000}^{1}$	$\underline{3.60000}^{3}$
Microsecond	1.15741^{-11}	2.77778^{-10}	$\underline{1.00000}$	$\underline{1.00000}^{-3}$	1.66667^{-8}	$\underline{1.00000}^{-6}$
Millisecond	1.15741^{-8}	2.77778^{-7}	$\underline{1.00000}^{3}$	$\underline{1.00000}$	1.66667^{-5}	$\underline{1.00000}^{-3}$
Minute	6.94444^{-4}	1.66667^{-2}	$\underline{6.00000}^{7}$	$\underline{6.00000}^{4}$	$\underline{1.00000}$	$\underline{6.00000}^{1}$
Second	1.15741^{-5}	2.77778^{-4}	$\underline{1.00000}^{6}$	$\underline{1.00000}^{3}$	1.66666^{-2}	$\underline{1.00000}$

5. TIME

SPECIALIZED CONVERSION FACTORS

	Degree	Minute	Quadrant (right angle)	Radians	Revolutions	Seconds
Degree	$\underline{1.00000}$	$\underline{6.00000}^{1}$	1.11111^{-2}	1.74533^{-2}	2.77778^{-3}	$\underline{3.60000}^{3}$
Minute	1.66667^{-2}	$\underline{1.00000}$	1.85185^{-4}	2.90889^{-4}	4.62963^{-5}	$\underline{6.00000}^{1}$
Quadrants (right angle)	$\underline{9.00000}^{1}$	$\underline{5.40000}^{3}$	$\underline{1.00000}$	1.57080	$\underline{2.50000}^{-1}$	$\underline{3.24000}^{5}$
Radians	5.72958^{1}	3.43775^{3}	6.36620^{-1}	$\underline{1.00000}$	1.59155^{-1}	2.06265^{5}
Revolutions	$\underline{3.60000}^{2}$	$\underline{2.16000}^{4}$	$\underline{4.00000}$	6.28320	$\underline{1.00000}$	$\underline{1.29600}^{6}$
Seconds	2.77777^{-4}	1.66667^{-2}	3.08642^{-6}	4.84815^{-6}	7.71605^{-7}	$\underline{1.00000}$

6. ANGLE

SPECIALIZED CONVERSION FACTORS

	cm/sec	ft/min	ft/sec	Kilometer/hr	Knot	Meter/min	Meter/sec	Mile/hr
Centimeter/second	1.00000	1.96850	3.28084^{-2}	3.60000^{-2}	1.94384^{-2}	6.00000^{-1}	1.00000^{-2}	2.23694^{-2}
Feet/minute	5.08000^{-1}	1.00000	1.66667^{-2}	1.82880^{-2}	9.87473^{-3}	3.04800^{-1}	5.08000^{-3}	1.13636^{-2}
Feet/second	3.04800^{1}	6.00000^{1}	1.00000	1.09728	5.92484^{-1}	1.82880^{1}	3.04800^{-1}	6.81818^{-1}
Kilometer/hour	2.77778^{1}	5.46807^{1}	9.11344^{-1}	1.00000	5.39957^{-1}	1.66667^{1}	2.77778^{-1}	6.21371^{-1}
Knot*	5.14444^{1}	1.01268^{2}	1.68781	1.85200	1.00000	3.08667^{1}	5.14444^{-1}	1.15078
Meter/minute	1.66667	3.28084	5.46807^{-2}	6.00000^{-2}	3.23974^{-2}	1.00000	1.66667^{-2}	3.72823^{-2}
Meter/second	1.00000^{2}	1.96850^{2}	3.28084	3.60000	1.94384	6.00000^{1}	1.00000	2.23694
Mile/hour	4.47040^{1}	8.80000^{1}	1.46667	1.60934	8.68976^{-1}	2.68224^{1}	4.47040^{-1}	1.00000

*One knot = one nautical mile per hour

7. VELOCITY

SPECIALIZED CONVERSION FACTORS

	Dyne	Gram force	Kilogram force	Newton	Poundal	Pound force
Dyne	1.00000	1.01972^{-3}	1.01972^{-6}	1.00000^{-5}	7.23301^{-5}	2.24809^{-6}
Gram force	9.80665^{2}	1.00000	1.00000^{-3}	9.80665^{-3}	7.09316^{-2}	2.20462^{-3}
Kilogram force	9.80665^{5}	1.00000^{3}	1.00000	9.80665	7.09316^{1}	2.20462
Newton	1.00000^{5}	1.01972^{2}	1.01972^{-1}	1.00000	7.23301	2.24809^{-1}
Poundal	1.38255^{4}	1.40981^{1}	1.40981^{-2}	1.38255^{-1}	1.00000	3.10809^{-2}
Pound force	4.44822^{5}	4.53594^{2}	4.53594^{-1}	4.44822	3.21740^{1}	1.00000

8. FORCE

SPECIALIZED CONVERSION FACTORS

	Standard Atmosphere	Bar**	Dynes/cm^2 (Barye)	Feet Water at 60°F*	Gm$_f$/cm^2	Inches Hg at 32°F*	Inches Water at 60°F*	Kg$_f$/cm^2	Lb$_f$/ft^2	Lb$_f$/in.^{2}	Micron Hg at 32°F*	mm Hg at 32°F*
Standard Atmosphere	1.00000	1.01325	1.01325^{6}	3.39320^{1}	1.03323^{3}	2.99213^{1}	4.07184^{2}	1.03323	2.11622^{3}	1.46959^{1}	7.60000^{5}	7.60000^{2}
Bar**	9.86923^{-1}	1.00000	1.00000^{6}	3.34882^{1}	1.01972^{3}	2.95300^{1}	4.01859^{2}	1.01972	2.08854^{3}	1.45038^{1}	7.50062^{5}	7.50062^{2}
Dynes/Centimeter^2 (Barye)	9.86923^{-7}	1.00000^{-6}	1.00000	3.34882^{-5}	1.01972^{-3}	2.95300^{-5}	4.01859^{-4}	1.01972^{-6}	2.08854^{-3}	1.45038^{-5}	7.50062^{-1}	7.50062^{-4}
Feet Water (at 60°F)*	2.94707^{-2}	2.98612^{-2}	2.98612^{4}	1.00000	3.04500^{1}	8.81801^{-1}	1.20000^{1}	3.04500^{-2}	6.23664^{1}	4.33100^{-1}	2.23977^{4}	2.23977^{1}
Gram$_{force}$/Centimeter^2	9.67841^{-4}	9.80665^{-4}	9.80665^{2}	3.28408^{-2}	1.00000	2.89590^{-2}	3.94089^{-1}	1.00000^{-3}	2.04816	1.42233^{-2}	7.35559^{2}	7.35559^{-1}
Inches Mercury at 32°F*	3.34211^{-2}	3.38639^{-2}	3.38639^{4}	1.13404	3.45315^{1}	1.00000	1.36085^{1}	3.45315^{-2}	7.07262^{1}	4.91154^{-1}	2.54000^{4}	2.54000^{1}
Inches Water at 60°F*	2.45589^{-3}	2.48843^{-3}	2.48843^{3}	8.33333^{-2}	2.53750	7.34834^{-2}	1.00000	2.53750^{-3}	5.19720	3.60917^{-2}	1.86648^{3}	1.86648
Kilogram$_{force}$/Centimeter^2	9.67841^{-1}	9.80665^{-1}	9.80665^{5}	3.28408^{1}	1.00000^{3}	2.89590^{1}	3.94089^{2}	1.00000	2.04816^{3}	1.42233^{1}	7.35559^{5}	7.35559^{2}
Pound$_{force}$/Feet^2	4.72541^{-4}	4.78803^{-4}	4.78803^{2}	1.60343^{-2}	4.88243^{-1}	1.41390^{-2}	1.92411^{-1}	4.88243^{-4}	1.00000	6.94444^{-3}	3.59131^{2}	3.59131^{-1}
Pound$_{force}$/Inch^2	6.80460^{-2}	6.89476^{-2}	6.89476^{4}	2.30894	7.03070^{1}	2.03602	2.77072^{1}	7.03070^{-2}	1.44000^{2}	1.00000	5.17149^{4}	5.17149^{1}
Microns Mercury at 32°F*	1.31579^{-6}	1.33322^{-6}	1.33322	4.46474^{-5}	1.35951^{-3}	3.93701^{-5}	5.35768^{-4}	1.35951^{-6}	2.78450^{-3}	1.93368^{-5}	1.00000	1.00000^{-3}
Millimeters Mercury at 32°F*	1.31579^{-3}	1.33322^{-3}	1.33322^{3}	4.46474^{-2}	1.35951	3.93701^{-2}	5.35768^{-1}	1.35951^{-3}	2.78450	1.93368^{-2}	1.00000^{3}	1.00000

*For g = 980.665 centimeters per second^2

**Some writers erroneously use the term bar for barye.

9. PRESSURE

SPECIALIZED CONVERSION FACTORS

	Btu	I.T. Calorie	electron volt	erg (dyne-cm)	ft-lb_f	gm_fcm	hp hr (Mech)	ab. Joule	kilocalorie	kg_f m	kw hr	watt hr	ft poundal
Btu	1.00000	2.51996^{2}	6.58577^{21}	1.05504^{10}	7.78158^{2}	1.07584^{7}	3.93009^{-4}	1.05504^{3}	2.51996^{-1}	1.07584^{2}	2.93067^{-4}	2.93067^{-1}	2.50365^{4}
I.T. Calorie	3.96832^{-3}	1.00000	2.61344^{19}	4.18674^{7}	3.08798	4.26928^{4}	1.55958^{-6}	4.18674	1.00000^{-3}	4.26928^{-1}	1.16298^{-6}	1.16298^{-3}	9.93528^{1}
electron volt	1.51842^{-22}	3.82637^{-20}	1.00000	1.60200^{-12}	1.18157^{-19}	1.63358^{-15}	5.96755^{-26}	1.60200^{-19}	3.82637^{-23}	1.63358^{-20}	4.45000^{-26}	4.45000^{-23}	3.80160^{-18}
erg (dyne-cm)	9.47831^{-11}	2.38849^{-8}	6.24220^{11}	1.00000	7.37562^{-8}	1.01972^{-3}	3.72506^{-14}	1.00000^{-7}	2.38849^{-11}	1.01972^{-8}	2.77778^{-14}	2.77778^{-11}	2.37304^{-6}
ft-lb_f	1.28509^{-3}	3.23836^{-1}	8.46328^{18}	1.35582^{7}	1.00000	1.38255^{4}	5.05050^{-7}	1.35582	3.23836^{-4}	1.38255^{-1}	3.76616^{-7}	3.76616^{-4}	3.21740^{1}
$gram_f$ cm	9.29505^{-8}	2.34231^{-5}	6.12150^{14}	9.80665^{2}	7.23301^{-5}	1.00000	3.65304^{-11}	9.80665^{-5}	2.34231^{-8}	1.00000^{-5}	2.72407^{-11}	2.72407^{-8}	2.32715^{-3}
hp hr (Mech)	2.54447^{3}	6.41196^{5}	1.67573^{25}	2.68452^{13}	1.98000^{6}	2.73745^{10}	1.00000	2.68452^{6}	6.41196^{2}	2.73745^{5}	7.45700^{-1}	7.45700^{2}	6.37046^{7}
ab. Joule (Watt sec)	9.47831^{-4}	2.38849^{-1}	6.24220^{18}	1.00000^{7}	7.37562^{-1}	1.01972^{4}	3.72506^{-7}	1.00000	2.38849^{-4}	1.01972^{-1}	2.77778^{-7}	2.77778^{-4}	2.37304^{1}
kilocalorie	3.96832	1.00000^{3}	2.61344^{22}	4.18674^{10}	3.08798^{3}	4.26928^{7}	1.55958^{-3}	4.18674^{3}	1.00000	4.26928^{2}	1.16298^{-3}	1.16298	9.93528^{4}
kg_f m	9.29505^{-3}	2.34231	6.12150^{19}	9.80665^{7}	7.23301	1.00000^{5}	3.65304^{-6}	9.80665	2.34231^{-3}	1.00000	2.72407^{-6}	2.72407^{-3}	2.32715^{2}
kw hr	3.41219^{3}	8.59858^{5}	2.24719^{25}	3.60000^{13}	2.65522^{6}	3.67098^{10}	1.34102	3.60000^{6}	8.59858^{2}	3.67098^{5}	1.00000	1.00000^{3}	8.54293^{7}
watt hr	3.41219	8.59858^{2}	2.24719^{22}	3.60000^{10}	2.65522^{3}	3.67098^{7}	1.34102^{-3}	3.60000^{3}	8.59858^{-1}	3.67098^{2}	1.00000^{-3}	1.00000	8.54293^{4}
ft poundal	3.99417^{-5}	1.00651^{-2}	2.63047^{17}	4.21401^{5}	3.10810^{-2}	4.29710^{2}	1.56974^{-8}	4.21401^{-2}	1.00651^{-5}	4.29710^{-3}	1.17056^{-8}	1.17056^{-5}	1.00000

Definitions: $\frac{1\ Btu}{^{o}F\ lb_m} = \frac{1\ I.T.\ Cal}{^{o}C\ gm}$

1 I.T.Cal = 1/860 int. watt hr

1 int. watt = 1.000165 ab. watt

1 Btu_{mean} = 1055.8 absolute joules

1 Btu_{39}°F = 1060 absolute joules

1 Btu_{60}°F = 1054.6 absolute joules

I.T. Btu = 1055.04 absolute joules

I.T. Cal_{15}°C = 4.1854 absolute joules

I.T. Calorie = 4.18674 absolute joules

1 Cal_{mean} = 4.190 absolute joules

1 Cal_{20}°C = 4.181 absolute joules

1 Thermochemical Calorie = 4.1840 absolute joules

1 International Joule = 1.000165 absolute joules

1 I.T. Calorie = 1/860 international watt hour

Kilocalorie or large calorie = 1000 calories

10. ENERGY

SPECIALIZED CONVERSION FACTORS

	Btu/hr	Btu/min	Btu/sec	I.T.Cal/hr	I.T.Cal/min	I.T.Cal/sec	erg/sec	ft-lb_f/min	ft-lb_f/sec	hp (Elec)	hp (Mech)	hp (Metric)	kg_fm/sec	kw	w
Btu/hr	1.00000	1.66667^{-2}	2.77778^{-4}	2.51996^{2}	4.19993	6.99988^{-2}	2.93067^{6}	1.29693^{1}	2.16155^{-1}	3.92851^{-4}	3.93009^{-4}	3.98460^{-4}	2.98845^{-2}	2.93067^{-4}	2.93067^{-1}
Btu/min	6.00000^{1}	1.00000	1.66667^{-2}	1.51197^{4}	2.51996^{2}	4.19993	1.75840^{8}	7.78158^{2}	1.29693^{1}	2.35711^{-2}	2.35805^{-2}	2.39076^{-2}	1.79307	1.75840^{-2}	1.75840^{1}
Btu/sec	3.60000^{3}	6.0000^{1}	1.00000	9.07183^{5}	1.51197^{4}	2.51996^{2}	1.05504^{10}	4.66894^{4}	7.78158^{2}	1.41426	1.41483	1.43446	1.07584^{2}	1.05504	1.05504^{3}
I.T.Cal/hr	3.96832^{-3}	6.61387^{-5}	1.10231^{-6}	1.00000	1.66667^{-2}	2.77778^{-4}	1.16298^{4}	5.14663^{-2}	8.57772^{-4}	1.55896^{-6}	1.55958^{-6}	1.58122^{-6}	1.18591^{-4}	1.16298^{-6}	1.16298^{-3}
I.T.Cal/min	2.38099^{-1}	3.96832^{-3}	6.61387^{-5}	6.00000^{1}	1.00000	1.66667^{-2}	6.97790^{5}	3.08798	5.14663^{-2}	9.35376^{-5}	9.35751^{-5}	9.48730^{-5}	7.11547^{-3}	6.97790^{-5}	6.97790^{-2}
I.T.Cal/sec	1.42859^{1}	2.38100^{-1}	3.96832^{-3}	3.60000^{3}	6.00000^{1}	1.00000	4.18674^{7}	1.85279^{2}	3.08798	5.61225^{-3}	5.61451^{-3}	5.69238^{-3}	4.26928^{-1}	4.18674^{-3}	4.18674
erg/sec	3.41219^{-7}	5.68699^{-9}	9.47831^{-11}	8.59858^{-5}	1.43310^{-6}	2.38849^{-8}	1.00000	4.42537^{-6}	7.37562^{-8}	1.34048^{-10}	1.34102^{-10}	1.35962^{-10}	1.01972^{-8}	1.00000^{-10}	1.00000^{-7}
ft-lb_f/min	7.71052^{-2}	1.28509^{-3}	2.14181^{-5}	1.94302^{1}	3.23836^{-1}	5.39727^{-3}	2.25970^{5}	1.00000	1.66667^{-2}	3.02909^{-5}	3.03030^{-5}	3.07233^{-5}	2.30425^{-3}	2.25970^{-5}	2.25970^{-2}
ft-lb_f/sec	4.62631	7.71052^{-2}	1.28509^{-3}	1.16581^{3}	1.94302^{1}	3.23836^{-1}	1.35582^{7}	6.00000^{1}	1.00000	1.81745^{-3}	1.81818^{-3}	1.84340^{-3}	1.38255^{-1}	1.35582^{-3}	1.35582
hp (Elec)	2.54549^{3}	4.24249^{1}	7.07081^{-1}	6.41453^{5}	1.06909^{4}	1.78182^{2}	7.46000^{9}	3.30132^{4}	5.50221^{2}	1.00000	1.00040	1.01427	7.60707^{1}	7.46000^{-1}	7.46000^{2}
hp (Mech)	2.54447^{3}	4.24079^{1}	7.06798^{-1}	6.41196^{5}	1.06866^{4}	1.78110^{2}	7.45701^{9}	3.30000^{4}	5.50000^{2}	9.99599^{-1}	1.00000	1.01387	7.60402^{1}	7.45701^{-1}	7.45701^{2}
hp (Metric)	2.50966^{3}	4.18277^{1}	6.97129^{-1}	6.32424^{5}	1.05404^{4}	1.75673^{2}	7.35500^{9}	3.25486^{4}	5.42476^{2}	9.85924^{-1}	9.86320^{-1}	1.00000	7.50000^{1}	7.35500^{-1}	7.35500^{2}
kg_fm/sec	3.34622^{1}	5.57703^{-1}	9.29505^{-3}	8.43233^{3}	1.40539^{2}	2.34231	9.80665^{7}	4.33981^{2}	7.23301	1.31456^{-2}	1.31509^{-2}	1.33333^{-2}	1.00000	9.80665^{-3}	9.80665
kilowatt	3.41219^{3}	5.68699^{1}	9.47831^{-1}	8.59858^{5}	1.43310^{4}	2.38849^{2}	1.00000^{10}	4.42537^{4}	7.37562^{2}	1.34048	1.34102	1.35962	1.01972^{2}	1.00000	1.00000^{3}
watt	3.41219	5.68699^{-2}	9.47831^{-4}	8.59858^{2}	1.43310^{1}	2.38849^{-1}	1.00000^{7}	4.42537^{1}	7.37562^{-1}	1.34048^{-3}	1.34102^{-3}	1.35962^{-3}	1.01972^{-1}	1.00000^{-3}	1.00000

11. POWER

SPECIALIZED CONVERSION FACTORS

	Gm_m/sec	Kg_m/sec	Lb_m/hr	Lb_m/min	Lb_m/sec	Slug/sec
Gm_m/sec	$\underline{1.00000}$	$\underline{1.00000}^{-3}$	7.93664	1.32277^{-1}	2.20462^{-3}	6.85218^{-5}
Kg_m/sec	$\underline{1.00000}^{3}$	$\underline{1.00000}$	7.93664^{3}	1.32277^{2}	2.20462	6.85218^{-2}
Lb_m/hr	1.25998^{-1}	1.25998^{-4}	$\underline{1.00000}$	1.66667^{-2}	2.77778^{-4}	8.63360^{-6}
Lb_m/min	7.55987	7.55987^{-3}	$\underline{6.00000}^{1}$	$\underline{1.00000}$	1.66667^{-2}	5.18016^{-4}
Lb_m/sec	4.53592^{2}	4.53592^{-1}	$\underline{3.60000}^{3}$	$\underline{6.00000}^{1}$	$\underline{1.00000}$	3.10809^{-2}
Slug/sec	1.45939^{4}	1.45939^{1}	1.15826^{5}	1.93044^{3}	3.21740^{1}	$\underline{1.00000}$

12. MASS FLOW RATE

SPECIALIZED CONVERSION FACTORS

	Cm^3/sec	Ft^3/min	Ft^3/sec	Gal/min	Liter/min	Liter/sec	M^3/hr	M^3/min
Cm^3/sec	1.00000	2.11888^{-3}	3.53147^{-5}	1.58503^{-2}	5.99983^{-2}	9.99972^{-4}	3.60000^{-3}	6.00000^{-5}
Ft^3/min	4.71947^{2}	1.00000	1.66667^{-2}	7.48052	2.83160^{1}	4.71934^{-1}	1.69901	2.83168^{-2}
Ft^3/sec	2.83168^{4}	6.00000^{1}	1.00000	4.48831^{2}	1.69896^{3}	2.83160^{1}	1.01941^{2}	1.69901
Gal/min	6.30902^{1}	1.33680^{-1}	2.22801^{-3}	1.00000	3.78530	6.30884^{-2}	2.27125^{-1}	3.78541^{-3}
Liter/min	1.66671^{1}	3.53156^{-2}	5.88594^{-4}	2.64179^{-1}	1.00000	1.66667^{-2}	6.00017^{-2}	1.00003^{-3}
Liter/sec	1.00003^{3}	2.11894	3.53156^{-2}	1.58508^{1}	6.00000^{1}	1.00000	3.60010	6.00017^{-2}
M^3/hr	2.77778^{2}	5.88578^{-1}	9.80963^{-3}	4.40287	1.66662^{1}	2.77770^{-1}	1.00000	1.66667^{-2}
M^3/min	1.66667^{4}	3.53147^{1}	5.88578^{-1}	2.64172^{2}	9.99972^{2}	1.66662^{1}	6.00000^{1}	1.00000

13. PUMPING SPEED

SPECIALIZED CONVERSION FACTORS

To convert from the units below to those on the right, perform the indicated operations in order.	°C	°F	°K	°R
°C	x 1	x 9/5 + 32	+ 273.15	x 9/5 + 491.67
°F	- 32 x 5/9	x 1	x 5/9 + 255.372	+ 459.67
°K	- 273.15	x 9/5 - 459.67	x 1	x 9/5
°R	x 5/9 - 273.15	- 459.67	x 5/9	x 1

*Based on the thermodynamic temperature scale as defined by the Tenth General Conference on Weights and Measures meeting at Paris in October 1954.

Temperature of triple point of water = 273.16°K = 491.688°R = 32.018°F = 0.01°C

Temperature of ice point of water = 273.15°K = 491.67°R = 0°C = 32°F

14. TEMPERATURE

ALTITUDE DATA

Altitude (feet)	Temperature °F	Pressure mm Hg	Pressure psi
0	59.000	759.99	14.696
500	57.217	746.76	14.440
1000	55.434	733.53	14.184
1500	53.652	720.27	13.928
2000	51.869	707.03	13.672
2500	50.086	693.80	13.416
3000	48.304	681.51	13.178
3500	46.521	669.24	12.941
4000	44.739	656.95	12.703
4500	42.956	644.68	12.466
5000	41.174	632.38	12.228
5500	39.392	621.00	12.008
6000	37.610	609.63	11.788
6500	35.827	598.22	11.568
7000	34.045	586.84	11.348
7500	32.263	575.46	11.128
8000	30.481	564.92	10.924
8500	28.700	554.38	10.720
9000	26.918	543.84	10.516
9500	25.137	533.30	10.312
10000	23.355	522.75	10.108
10500	21.574	513.00	9.9200
11000	19.793	503.28	9.7318
11500	18.012	493.52	9.5432
12000	16.231	483.79	9.3551
12500	14.450	474.04	9.1665
13000	12.669	465.05	8.9926
13500	10.888	456.06	8.8188
14000	9.108	447.07	8.6449
14500	7.327	438.07	8.4710
15000	5.546	429.08	8.2972

ALTITUDE DATA

Altitude (feet)	Temperature °F	Pressure mm Hg	psi
15500	3.766	420.80	8.1370
16000	1.985	412.52	7.9769
16500	0.205	404.22	7.8163
17000	- 1.576	395.94	7.6562
17500	- 3.356	387.65	7.4961
18000	- 5.136	380.03	7.3487
18500	- 6.916	372.41	7.2014
19000	- 8.695	364.77	7.0535
19500	-10.475	357.15	6.9062
20000	-12.255	349.53	6.7589
21000	-15.814	335.51	6.4877
22000	-19.373	321.51	6.2171
23000	-22.931	308.08	5.9573
24000	-26.489	295.25	5.7092
25000	-30.047	282.40	5.4607
26000	-33.604	270.64	5.2333
27000	-37.161	258.88	5.0059
28000	-40.718	247.62	4.7883
29000	-44.275	236.88	4.5805
30000	-47.831	226.13	4.3727
31000	-51.387	216.33	4.1832
32000	-54.942	206.53	3.9937
33000	-58.497	197.17	3.8127
34000	-62.052	188.25	3.6402
35000	-65.607	179.33	3.4677
36000	-67.244	171.25	3.3115
37000	-68.881	163.18	3.1554
38000	---	155.55	3.0078
39000	---	148.37	2.8690
40000	-69.700	141.18	2.7301

ALTITUDE DATA

Altitude (feet)	Temperature °F	Pressure mm Hg	psi
41000	---	134.81	2.6069
42000	---	128.44	2.4837
43000	---	122.43	2.3675
44000	---	116.78	2.2582
45000	-69.700	111.13	2.1490
46000	---	106.12	2.0520
47000	---	101.11	1.9552
48000	---	96.380	1.8637
49000	---	91.933	1.7777
50000	-69.700	87.488	1.6918
51000	---	83.543	1.6155
52000	---	79.599	1.5392
53000	---	75.877	1.4672
54000	---	72.380	1.3996
55000	-69.700	68.882	1.3320
56000	---	65.778	1.2720
57000	---	62.674	1.2119
58000	---	59.746	1.1553
59000	---	56.993	1.1021
60000	-69.700	54.239	1.0488
61000	---	51.069	9.8753×10^{-1}
62000	---	47.902	9.2628
63000	---	44.732	8.6498
64000	---	41.562	8.0368
65000	---	38.395	7.4244
70000	-69.700	33.640	6.5049
80000	-69.700	20.874	4.0365
90000	-57.204	13.033	2.5202
100000	-40.893	8.2906	1.6031
150000	40.425	1.0988	2.1248×10^{-2}
200000	- 10.69	1.6934	3.2744×10^{-3}
300000	-160.5	7.605×10^{-4}	1.471×10^{-5}
400000	464.2	1.351×10^{-5}	2.612×10^{-7}
500000	1473	3.721×10^{-6}	7.195×10^{-8}
1000000	2104	1.777×10^{-7}	3.437×10^{-9}
2000000	2604	3.612×10^{-9}	6.984×10^{-11}

USEFUL PHYSICAL CONSTANTS

Acceleration of gravity (g)	= 32.17 ft/sec^2
	= 980.6 cm/sec^2
Velocity of sound in dry air @ 0°C and 1 atmos.	= 33,136 cm/seccnd
	= 1,089 feet/second
Heat of fusion of water	= 79.7 calories/gram
	= 144 Btu/pound
Heat of vaporization of water @ 1.0 atmos.	= 540 calories/gram
	= 970 Btu/pound
Specific heat of air	= Cp = 0.238 cal/gram (°C)
Density of air @ 0°C and 760 mm	= 0.991293 grams/cubic cm
Velocity of light (c)	= 2.997902x10^{10} cm/sec
Avogadro's number (N)	= 6.061x10^{23} molecules/gram-mole
Pi (π)	= 3.14159265
Naperian-logarithm base	= 2.71828183
Radiation absorbtion dose (rad)	= 1.0x10^{2} ergs/gram
Roentgen (r)	= 8.3x10^{-1} rads